Army Research Laboratory

50^{th} Anniversary Celebration: 46^{th} Sagamore Army Materials Research Conference on Advances and Needs in Multi-Spectral Transparent Materials Technology

by James M. Sands and James W. McCauley

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50th Anniversary Celebration: 46th Sagamore Army Materials Research Conference on Advances and Needs in Multi-Spectral Transparent Materials Technology

James M. Sands and James W. McCauley
Weapons and Materials Research Directorate, ARL

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14. ABSTRACT
Since 1954, the Sagamore Army Materials Research Conferences has brought together scientists and engineers from government, industry, and academia for in-depth discussions of cutting edge materials technology issues of critical importance to the U.S. Army community. The 46th Sagamore Army Materials Research Conference continued this tradition with a focus on “Advances and Needs in Multi-Spectral Transparent Materials Technology.” Held at the Harbourtowne Golf Resort and Conference Center, St. Michaels, MD, on May 9–12, 2005, the objective of this conference was to review the applications, requirements, and major technical barriers of multi-spectral transparent materials for sensor protection, ground and air vehicle ballistic protection, personnel protection, and infrastructure survivability. The conference proceedings, documented in this report, included presentation media along with selected papers and supporting content that highlight the performance and capabilities requirements of the embedded Army systems in Current and Future Forces. The multi-spectral transparent materials technology needs include transparent armor, phased array radar, displays, electromagnetic windows and domes, and polycrystalline lasers. The presentations focus on processing, characterization, property testing, and system requirements of advanced ceramic and polymer systems to enable the cost-effective manufacturing of high quality, reproducible materials for these applications. These proceedings demonstrate both the effective communication of critical technology needs within the industrial community as well as continued opportunities for advancement of these technologies for military applications.

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Executive Summary

Objective

Since 1954, the Sagamore Army Materials Research Conferences has brought together scientists and engineers from government, industry, and universities for in-depth discussions of cutting edge materials technology issues of critical importance to the Army community. As threats to the United States have become more asymmetric, the U.S. Army has embarked on a transformation to adapt its operational strategies to better protect the nation. General Peter J. Schoomaker, Chief of Staff of the U.S. Army, has laid out a vision of a more relevant and ready Army, focused on a "capabilities-based modular, flexible, and rapidly employable Joint-Army team" with the following cross-cutting characteristics: responsiveness, deployability, agility, versatility, lethality, survivability, and sustainability. Capability gaps are continually identified and prioritized to better focus the research and development (R&D) program. In many, if not most, of the cross-cutting characteristics and identified gaps, new and improved materials used in innovative designs are the enabling underpinnings for the evolutionary improvement of the Current Force as well as for the revolutionary invention of weapon systems for the Future Force. It was the objective of the 46th Sagamore Army Materials Research Conference, held May 9–12, 2005, to review the applications, requirements, and major technical barriers of multi-spectral transparent materials for sensor protection, ground and air vehicle ballistic protection, personnel protection, and infrastructure survivability.

Scope

The conference was organized to logically proceed from the performance/capabilities requirements of the embedded Army systems in the Current and Future Force toward the multi-spectral transparent materials technology needs required to close the identified gaps in transparent armor, phased array radar, displays, electromagnetic windows and domes, and polycrystalline lasers. The focus was on processing, characterization, property testing, and system requirements of advanced ceramic and polymer systems to enable the cost-effective manufacturing of high quality, reproducible materials for these applications. Current research and technology was highlighted as well as novel concepts that will help the Army prioritize future research and development efforts.

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1. Historic Background on the Army Sagamore Conference Series

In 1954 Dr. George Sachs of Syracuse University (SU) and Dr. R. Beeuwkes and Mr. N. Reed of the Ordnance Materials Research Office (OMRO) at the Watertown Arsenal, Watertown, MA, initiated the Sagamore Army Materials Research Conferences. The first conference was named the “Research Conference on Residual-Stress Problems in Practice” and was held at the Sagamore Conference Center on Sagamore Lake in the Adirondack Mountains of New York State during August 19–20, 1954. The conference consisted of 18 oral presentations with the attendees being welcomed by Dr. Finla G. Crawford, Vice-Chancellor, SU; and Col. B.S. Mesick, Ordnance Corps, USA, Commanding Officer, Watertown Arsenal, Watertown, MA. A book of proceedings was not prepared for this first conference, nor was it named the Sagamore Conference.

With the exception of the third conference in 1956, the conferences were held at the Sagamore Conference Center until 1977. The Conference Center (figures 1–4) is located on Sagamore Lake (formerly Shedd Lake), which was named after a character in Fenimore Cooper’s *Last of the Mohicans*. It is located near Raquette Lake in the Adirondack Mountains of New York State. It is one of the so-called Great Camps of the Adirondacks and was built by William West Durant during 1897–1901. It was purchased by Alfred G. Vanderbuilt in 1903 for a vacation retreat and then given to SU in 1954. In 1974, the Center was sold by SU. Beginning in 1977, the conference site moved to other locations. Table 1 summarizes this history.

Table 1. History of meeting locations for Sagamore conferences since inception.

Conference Year(s)	Location
1954	Sagamore Lodge, Adirondacks, NY
1956	Duke University, Durham, NC
1958–1976	Sagamore Lodge, Adirondacks, NY
1977–1980	Sagamore Hotel, Bolton Landing, Lake George, NY
1981–1982	Lake Placid, NY
1983–1985	Lake Luzerne, NY
1986	Burlington, VT
1987	Sagamore Hotel, Bolten Landing, Lake George, NY
1988	Manchester, NH
1989–1994	Plymouth, MA
1996	Wilmington, DE
1997	Baltimore, MD
1999	Easton, MD
2001	Harbourtowne Resort, St Michaels, MD
2005	Harbourtowne Resort, St Michaels, MD

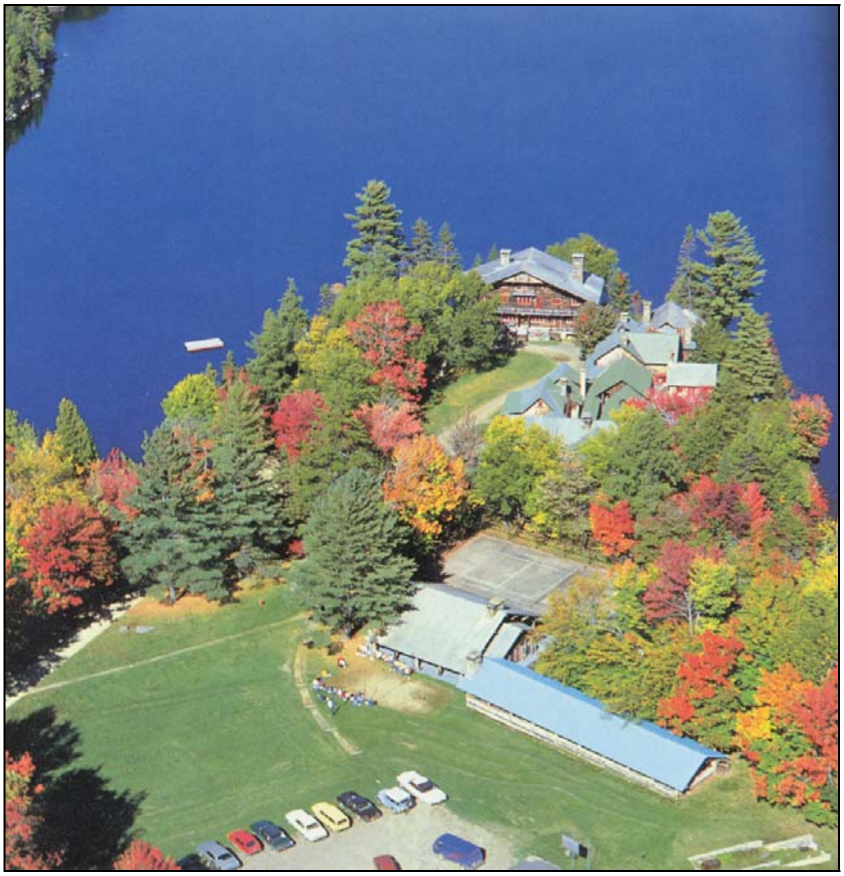


Figure 1. Aerial photo of the rustic Sagamore Lodge as it appeared in 1982 (Kaiser, 1982).

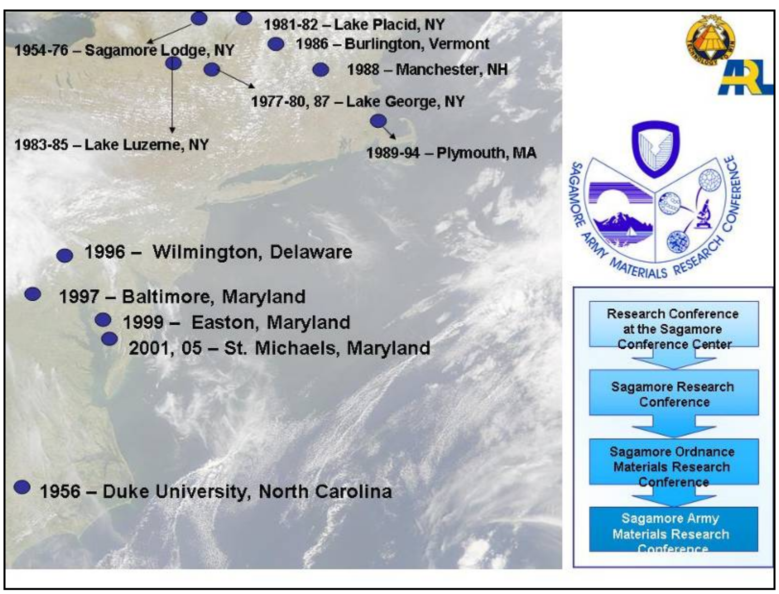


Figure 2. Sagamore Lodge in upstate New York is the origination of the Sagamore series of meetings; the meetings have since been held throughout the northeastern United States.

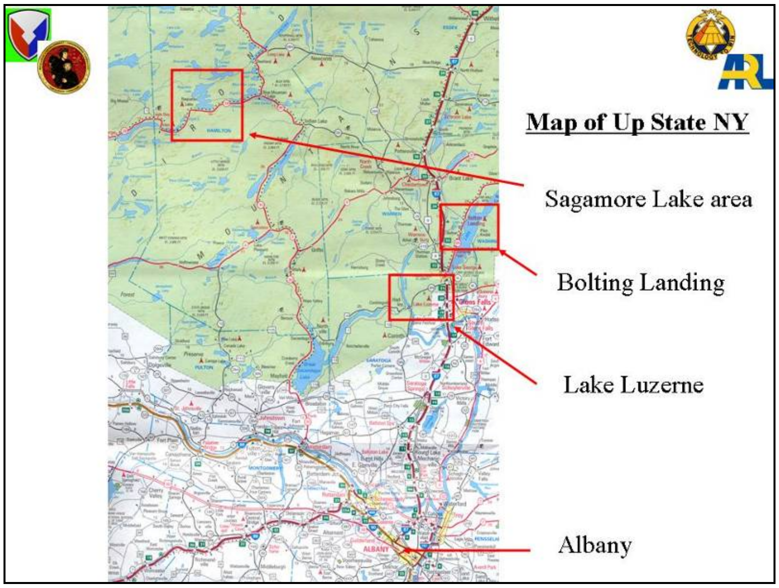


Figure 3. Presented is a map of upstate New York that shows the remoteness of the Sagamore Lake area; the remote nature of the meeting location facilitated much of the very personal exchange for which the Sagamore meeting series are noted.

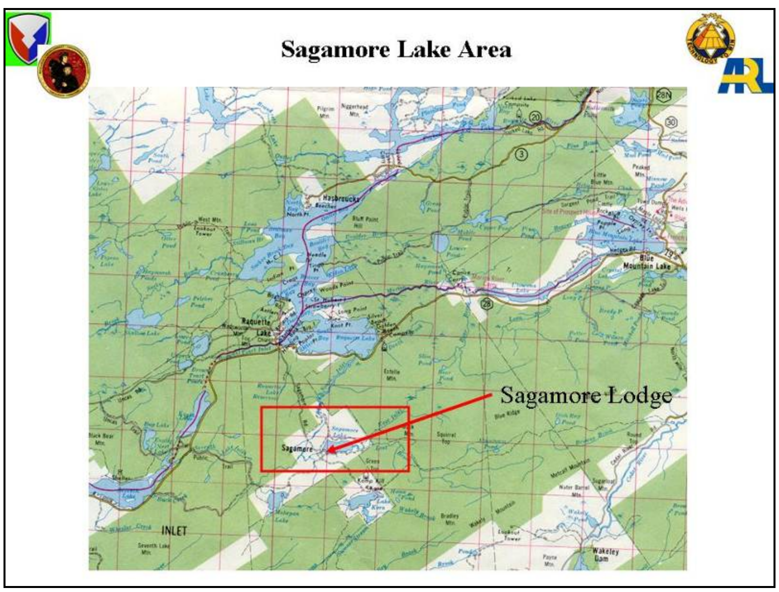


Figure 4. A zoomed-in view of the Sagamore lodge showing specific lake region details.

There was a lot of activity in materials research activities at the Watertown Arsenal, MA, in 1954. The Army Chief of Ordnance moved OMRO from the Washington, DC, area to the Watertown Arsenal, MA, in order to plan and administer supporting fundamental materials research at Watertown and other Army Laboratories. Also in 1954, a new Metals Processing Laboratory, the General Thomas J. Rodman Laboratory, was established at the Watertown Arsenal, MA. Years later (1996), when the Watertown Laboratories (Materials Directorate of the U.S. Army Research Laboratory (ARL)) were moved to a new facility at Aberdeen Proving Ground (APG), MD, this new facility was called the Rodman Materials Research Laboratory.

During August 24–26, 1955, the second conference (now called the Sagamore Research Conference) was convened on “Strength Limitations of Metals.” Again, it was conducted at the Sagamore Conference Center in collaboration with Professor George Sachs of the SU Research Institute and sponsored by the U.S. Army Ordnance Corps. Proceedings were published for this conference and for all of the conferences that followed.

In 1956 the conference was renamed the Sagamore Ordnance Materials Research Conference and held at Duke University on December 5–7, 1956, since the Office of Ordnance Research (OOR, now named the Army Research Office (ARO) in Research Triangle Park, NC) was located on the Duke Campus since its founding in 1951. This conference focused on “Materials Evaluation in Relation to Component Behavior” and was co-sponsored by OMRO and OOR and organized by the following committee: G. Sachs, SU Research Institute; Chairman, R. Beeukes, Jr., OMRO; P.R. Kosting, OOR; J. Lubahn, General Electric Company, Secretary; and N. L. Reed, OMRO. This would be the last time for many years that the conference was not held at the Sagamore Conference Center. As stated in the proceedings of these conferences, they “are intended to provide governmental and associated non-governmental groups with an up-to-the-minute correlated picture of the most recent advances, of probable future developments, and of the principles involved in a particularly important, but rather narrow field of metals technology.” From 1956 to 1960 the conferences were co-sponsored by the OMRO (Watertown) and the OOR (Duke).

The Fifth Sagamore Ordnance Materials Research Conference was co-sponsored by the Army Ballistic Missile Agency and focused on “Materials in Space Environment.” Professor George Sachs again chaired the organizing committee.

During August 18–21, 1959, Sachs from SU, with Beeuwkes and Reed from OMRO and others, organized the sixth conference on “Composite Materials and Composite Structures.” On October 29, 1960, Dr. George Sachs passed away and the following conference on “Mechanical and Metallurgical Behavior of Sheet Metals” was held in his honor at the Sagamore Conference Center on August 16–19, 1960. Dr. John Burke, OMRO (figure 5), became a member of the organizing committee for the first time, and continued as a major force for these conferences until 1980 (27th).

The following year, 1961, Professor Volker Weiss (figure 5) from SU started his association with these conferences, which lasted until 1984 (31st). N.L. Reed, OMRO, chaired this conference on “Mechanisms Operating in Metals at Elevated Temperatures.” The OMRO at Watertown was the sole sponsor of this conference and the others that followed. It was during this same year that the OOR at Duke was renamed the Army Research Office – Durham (AROD) due to an Army reorganization.

Figure 5. Dr. Volker Weiss is shown here (far right) enjoying a break during a previous Sagamore Conference meeting in New York. Others (from left to right) include Dr. John Burke (Deputy Director, Army Materials & Mechanics Research Center (AMMRC)), Mary Ann McCauley and Dr. James McCauley (second couple from left), Mrs. John Burke, Mrs. Ed Wright, and Dr. Ed Wright (Director, AMMRC).

In 1962, the OMRO at Watertown was renamed the U.S. Army Materials Research Agency. This was the year that the name of the conference changed to the Sagamore Army Materials Research Conference.

The organizing committee of the conferences from 1963 (10th) to 1968 (15th) consisted of J.J. Burke, N.L. Reed, and V. Weiss. With the exception of the 25th conference in 1978, which included Robert Mehrabian of the Massachusetts Institute of Technology (MIT), the conferences from 1969 (16th) to 1980 (27th) were organized by J.J. Burke and V. Weiss, at which time J.J. Burke stepped off the organizing committee; Weiss continued until 1984. At this point the conferences were organized on a year-to-year basis by scientists and engineers of the Watertown Materials Labs. A summary of all of the conferences is given in table 2.

Table 2. Thematic history of Sagamore research conferences since inception.

Conference Year – Number	Theme
1954 – 1^{st}	Residual Stresses
1955 – 2^{nd}	Strength Limitations of Metals
1956 – 3^{rd}	Materials Evaluation in Relation to Component Behavior
1957 – 4^{th}	High Temperature Materials, Their Strength Potentials and Limitations
1958 – 5^{th}	Materials in Space Environment
1959 – 6^{th}	Composite Materials and Composite Structures
1960 – 7^{th}	Mechanical and Metallurgical Behavior of Sheet Materials
1961 – 8^{th}	Mechanisms Operating in Metals at Elevated Temperatures
1962 – 9^{th}	Fundamentals of Deformation Processing
1963 – 10^{th}	Fatigue – An Interdisciplinary Approach
1964 – 11^{th}	Charge and Spin Density
1965 – 12^{th}	Strengthening Mechanisms, Metals and Ceramics
1966 – 13^{th}	Surface and Interfaces I: Physical and Chemical Characterizations
1967 – 14^{th}	Surfaces and Interfaces II: Physical and Mechanical Properties
1968 – 15^{th}	Ultrafine Grain Ceramics
1969 – 16^{th}	Ultrafine Grain Metals
1970 – 17^{th}	Shockwaves and the Mechanical Properties of Solids
1971 – 18^{th}	Powder Metallurgy for High-Performance Applications
1972 – 19^{th}	Block and Graft Copolymers
1973 – 20^{th}	Characterization of Materials in Research Ceramics and Polymers
1974 – 21^{st}	Advances in Deformation Processing
1975 – 22^{nd}	Application of Fracture Mechanics to Design
1976 – 23^{rd}	Non-destructive Evaluation of Materials
1977 – 24^{th}	Risk and Failure Analysis for Improved Performance and Reliability
1978 – 25^{th}	Recent Advances in Metals Processing
1979 – 26^{th}	Surface Treatments for Improved Performance and Properties
1980 – 27^{th}	Fatigue – Environment and Temperature Effects
1981 – 28^{th}	Residual Stress and Stress Relaxation
1982 – 29^{th}	Material Behavior under High Stress and Ultrahigh Loading Rates
1983 – 30^{th}	Innovations in Materials Processing
1984 – 31^{st}	Materials Characterization for Systems Performance and Reliability
1985 – 32^{nd}	Elastomers and Rubber Technology
1986 – 33^{rd}	Corrosion Prevention and Control
1987 – 34^{th}	Innovations in High Strength Steel Technology
1988 – 35^{th}	The Science and Technology of Adhesive bonding

Table 2. Thematic history of Sagamore research conferences since inception (continued).

Conference Year – Number	Theme
1989 – 36th	Thick Section Composite Technology
1990 – 37th	Structural Ceramics
1991 – 38th	Electromagnetic, Electro-Optical, and Electronic Materials
1992 – 39th	The Science and Technology of Fire Resistant Materials
1993 – 40th	Metallic Materials for Lightweight Applications
1994 – 41st	Intelligent Processing of Materials
1996 – 42nd	Gun Barrel Wear and Erosion
1997 – 43rd	Intelligent Processing and Inspection of Polymer Composite Materials
1999 – 44th	Nano-structured Materials
2001 – 45th	Armor Materials By Design
2005 – 46th	Advances and Needs in Multispectral Transparent Materials

Since their inception in 1954, the Materials Research Laboratories of the U.S. Army, with a variety of name and location changes associated with organizational growth, have organized and sponsored the conferences. The history of the sponsoring organization and significant changes is shown in table 3.

Table 3. Organizational changes associated with the Sagamore conference sponsor.

Year	Organization and Location
1954–1962	OMRO, Watertown, MA
1962–1967	Army Materials Research Agency, Watertown, MA
1967–1985	AMMRC, Watertown, MA
1985–1992	Army Materials Technology Laboratory, Watertown, MA
1992–1996	Materials Directorate, ARL, Watertown, MA
1996–present	Weapons Materials Division, Weapons and Materials Research Directorate, ARL, APG, MD

Throughout all the years, efforts were made to have the conferences focused on key issues in materials science and engineering that impact directly on current or future Army requirements, with topics selected after extensive discussions within and outside the Army. Efforts were made to bring in outstanding external speakers with new ideas, including international speakers. The idea being that the presentations and ensuing discussions would help guide the research programs. A Gordon conference style format and remote type of locations were used to stimulate interactions and discussions.

2. Keynote Address: A Personal Review of the Sagamore Conference Series History by Dr. Volker Weiss, Professor Emeritus of Engineering and Physics, Syracuse University

Note: What follows is the text of the address. Section 3 shows the slides from the briefing. All figures referenced in section 2 refer to figures shown in section 3.

Ladies and Gentlemen, Colleagues and friends,

When Jim McCauley asked if I would like to give an "after dinner speech" on the history and impact of the Sagamore Conferences, I accepted with delight (figure 6 and 7). Both because I have been involved with the conferences since before 1960 and, more importantly, because I believe that these kinds of intimate conferences contribute much to understanding and progress of our field, materials science and engineering. Obviously I cannot do justice to chronicle the accomplishments of 50—or actually 51—conferences. So I shall not abuse your patience and limit myself to observations about the origin of the Sagamore conference series and the earlier period. I would also like to attempt to assess the impact or potential impact these conferences had. Since this is an after-dinner speech, please allow me also some personal tales, not necessarily related to science and technology.

Figure 6. Dr. Volker Weiss (left) and Dr. James McCauley (right) at the 2005 Sagamore Conference in St. Michaels, MD.

The conference series has endured marvelously. This year we are celebrating the 50th Anniversary of the Sagamore Conferences.

At the time of the so-called first Sagamore Conference I was a graduate Student at Syracuse University, single and 25 years old. So you could say I am celebrating the 50th Anniversary of my 25th birthday.

In the early 50s conditions were favorable for Syracuse University to become a significant contributor to research in materials science.

The first was that George Sachs joined the faculty in 1952 (Figure 8). Here is one of his official portraits, probably the last one, taken just before the 1960 Sagamore Conference, which was dedicated to him. George Sachs was an internationally recognized metallurgist, famous for the well known Kurdjumov-Sachs orientation relationships between Austenite and Martensite, the Sachs boring-out turning-off method of residual stress measurements, author and coauthor of over 100 publications and several books, and much more. He came from Case Western where he had already been active in sponsored materials research, a relatively new trend in universities at the time.

The second was that in 1953 Syracuse University (SU) received as a gift the former Vanderbilt vacation estate Sagamore, in the central Adirondack Mountains in New York State, to be used as a conference center (Figure 9). It is a beautiful spot on a small peninsula into Sagamore Lake, as you can see from the aerial picture (Figure 10–12, Figure 13).

The camp and buildings were grand and elegant, one of the famous William West Durant camps built in 1897. The first time I saw Sagamore was in the spring of 1954, when my future wife, then the editor of SU's Alumni magazine, was asked to write a story about the new conference centers. In spite of its grandeur it was obvious that the camp was somewhat neglected and needed repairs. A group of visiting young engineers and technicians from Europe, who were here for practical training in industry and could not be placed because of strikes, was invited to help - and they did. Several of these students were my friends. At the conclusion of their work they were allowed to invite friends and we could party for two days, in late August 1954.

The First Sagamore Conference on Residual Stresses, sponsored by the Army Research Office and organized by Watertown Arsenal and Syracuse University, opened only a few days later, in September 1954. Since I was not invited and did not attend, nor have seen the proceedings, which have, I am told, just been compiled from Dr. Beeuwkes' notes, I do not know the details of the committee or the program; however, I am sure that Dr. Rainier Beeuwkes played a major role (Figure 14). Rainier Beeuwkes continued his involvement with the Sagamore Conferences, even beyond his retirement as chief scientist of the by then AMMRC.

In spite of its seeming informality [of the first Sagamore Conference], in retrospect, the conference was successful, so successful that it was considered as the start of an annual series, as is evident from the preface of the Second Sagamore Conference on Strength Limitations of Metals (Figure 15, Figure 16).

The program included an entire session devoted to fracture, a recurrent theme for many future Sagamore Conferences. It is quite certain that these contributed much to the development of Fracture Mechanics, as we know it today. George Irwin delivered a paper entitled "Onset of Fast Crack Propagation in High Strength Steels and Aluminum Alloys." In it he introduced the concept of "a crack extension 'force tendency'." It is a relatively compact paper, 11 double-spaced pages, five references, Griffith, Sneddon, Westergaard, Brossman and Kies (1954), and Karney, Chipman and Grant. No references to prior work by Irwin. In some later conversation with him I learned that the script, which he used as the symbol for the "crack extension force tendency" was chosen to honor Griffith. This paper may well have been his first public attempt to modify the Griffith concept so that it becomes applicable to real high strength structural materials. At that time we referred to these modifications as the "Griffith-Irwin" fracture concept. Section size effects on strength and hydrogen embrittlement were topics of major concern.

Yes, there were Proceedings, the first proceedings, put out by the "Syracuse University Research Institute." Report format was economical with a limited number of multi-lith copies (Figure 17).

And so the series was securely established. The Third conference dealt with Materials Evaluation in Relation to Component Behavior; the fourth with High Temperature Materials; the Fifth with Materials in Space Environments the Sixth with Composite Materials and the Seventh with Sheet Materials.

One can point to many contributions and opening of new avenues by these conferences. For example, the 1958 conference was on "Materials in Space Environments." The topic was chosen in rather rapid response to the launching of Sputnik on October 4, 1957. J. H. Garrett of the Department of Defense characterized the reaction of the USA in the opening paragraph of his welcoming address (Figure 18, Figure 19).

> "It is not quite a year since the progress of the first Sputnik across the skies awakened a startled world. In that year we have witnessed an almost unbelievable change of pace in the scope and pace of our defense research and engineering programs. We are today in the midst of a burst of creative energy that can only occur in times of great national stress."

The conference was cosponsored and strongly supported by the Army Ballistic Missile Agency, the Huntsville Alabama group.

To address all of these could make for a very long after dinner speech.

Let me just focus, as an example, not necessarily the most important one, on the contributions to our understanding of fracture mechanics, an example which also illustrates the character and openness of these conferences.

The sixth conference serves as such an example: It was prosaically devoted to sheet materials, however, the underlying need was for solid rocket fuel cases and fracture toughness was a primary concern (Figure 20-Figure 22). George Sachs and, naturally, our group in Syracuse, concentrating on the effects of notches with finite root radii, felt uncomfortable with Irwin's approach involving a stress singularity at the tip of a crack, having a root radius of zero, demanding that the stress there reaches infinity - coupled with a "thermodynamical" energy balance concept. The "Neuber School" suggested a critical maximum normal stress fracture criterion, i.e.,

$$\text{(net section stress) x (stress concentration factor) = constant.} \qquad (1)$$

Through happenstance we found a heat treatment that made a titanium alloy almost "ideally" brittle. With this material John G. Sessler (1960) could show data that fully agreed with this maximum stress failure criterion, to notches having root radii larger than 0.001 inches. The asymptotic approach to a constant notch strength for sharper root radii was explained with the help of Neuber's theory of sharp notches (Neuber 1958). Of course, tougher materials did not follow the predictions of this critical maximum stress failure criterion—and plasticity corrections, first those proposed by Hardrath and Ohman (1951) and later those referred to as the "Neuber Rule" (Neuber 1961),

$$K_\sigma * K_\varepsilon = K_t^2 \qquad (2)$$

were introduced, where K_σ is the true stress concentration factor, K_ε the true strain concentration factor, and K_t the elastic (geometric) stress concentration factor. The relation is similar to that found by Hutchinson (1968) for the stress and strain fields at the tip of a sharp crack in a nonlinear elastic solid. There were several papers using the Irwin Fracture mechanics approach. His own presentation was entitled "Plastic Zone near a Crack and Fracture Toughness." Again it was a rather compact paper, eight single spaced pages, five references, and seven figures. The references, four to Irwin or Irwin and Kies, and one to an ASTM committee report, indicate considerable activity on the "Griffith-Irwin Fracture Mechanics" since the 1955 and 1958 Sagamore Conferences. In the paper Irwin proposes to account for plasticity near the tip of a crack by adding part or all of the calculated plastic zone size to the crack length since the stress relaxation inside the plastic zone must be carried by the ligament. Sachs did not agree. Let me assure you that Sachs and Irwin had great respect for each other; both told me so—and I am sure they liked each other. Nevertheless in the following prepared discussion session George Sachs took strong exceptions to the "Griffith-Irwin" approach. Here are some excerpts:

> "The merit of Dr. Irwin's work is undisputed. However, I would like to take strong exception to the philosophy, which he expressed…My background is to a considerable extent in Applied Mechanics. For me, stress concentration effects, as defined by the theory of elasticity and calculated by Neuber, are more readily understandable than Dr. Irwin's calculations. I have discussed this problem with a number of scientists and have frequently been asked to act as council for defending the stress concentration approach.

> Griffith's theory is a thermodynamical approach and circumvents stress distributions…(it) is also not applicable to the effect of section size…nor does it lead to any conclusions relating to such phenomena as a fast rate of crack propagation, critical crack length and so forth…If the claim is made that these phenomena can be explained on the basis of a modified Griffith theory, this becomes a matter or religion, rather than of science: you either believe it, or you do not believe it."

Strong words—but George Sachs was never one to hold back his opinions. His comments created considerable excitement, which was further heightened by additional discussions pro and contra the Irwin or the notch approach. Rumors circulated that a special Irwin-Sachs debate would be scheduled for Wednesday afternoon, for which no sessions were scheduled to allow for group discussions, in combination with such activities as golf, tennis, swimming, hiking etc. No such public debate occurred and the two Georges left at the end of the conference as colleagues who had great respect for each other. Years later, after the sudden and unexpected death of George Sachs in October of the same year, when we reminisced about these events, George Irwin told me that he will cherish the memory of George Sachs by the events and remarks during the 1960 Sagamore Conference.

Being probably somewhat doubtful whether the Sagamore Conference series could continue at Sagamore without Sachs, the sponsors decided to scale back and plan a less ambitious Eighth Sagamore Conference for 1961 (Figure 23–Figure 24).

Five sessions of lectures on elevated temperature effects operating in metals followed by discussions were the structure. It worked, we published textbook-like proceedings, the sponsors were satisfied, and soon afterwards I was asked to participate in the planning of the Ninth Sagamore Research Conference on "Fundamentals of Deformation Processing" —a topic of concern not only to the Army but also to the Materials Advisory Board of the National Academy of Sciences (Figure 25–Figure 26).

The conference was really a great success and the topic became a recurrent theme of Sagamore Conferences. Attention was specifically drawn to power spinning, anisotropy and its effect on the yield strength, with special reference to titanium alloys, and, in later conferences to high strain rate and explosive forming and superplasticity.

Also, as you can see from the slides, the proceedings were published commercially in book form, from the ninth to the twentieth by Syracuse University Press and since by Plenum Press (Figure 27–Figure 30). They received wide national and international distributions. I frequently saw Sagamore Conference books in technical bookstores in Austria and Germany.

Another important recurrent theme, already introduced in the very early conferences was fracture and fatigue. These and later Sagamore conferences made significant contributions to our understanding of fracture, the development of standards for fracture toughness testing, and application of fracture mechanics to design and Failure Analysis (Figure 31–Figure 33).

Probably almost all materials topics of concern to the Department of Defense (DoD) were covered by the Sagamore Conferences, including such subjects as Solid State Physics fundamentals of materials at the 11th conference in 1964 on “Charge and Spin Density.” The materials list included metals and alloys, ceramics, polymers, elastomers, composite materials, and now transparent structural materials.

It would take a long time to report all significant contributions where Sagamore Conferences originated, stimulated or enhanced important developments. Moreover, my immediate contact with the conferences ended after the 31st conference, chaired by Dr. McCauley, on “Materials Characterization.” However, I would like to point to two more important recurring themes of Sagamore Conferences: “Strengthening Mechanisms” and “Ultrafine Grain Size Materials.” The second, 12th and 34th were devoted exclusively to the former, the 15th and 16th to the latter.

Strength Limitations of Metals was the topic of the 1955 Conference. Topics included electron microscopic evidence of the motion and reaction of dislocations by John Hirsch, now Sir John Hirsch, Grain size and phase transformation effects by Earl Parker and Eugene Klier, Section Size Effects by Jack Lubahn, Stress Concentration and Residual Stresses by Oscar Hoffman, Hydrogen Embrittlement by Nate Promisel, High Strength Steel properties at room and elevated temperatures by Abe Hurlich and Bill Brown and the already mentioned paper by George Irwin on Crack Propagation.

The 12th conference, in 1965, was entitled “Strengthening Mechanisms, Metals and Ceramics.” The scope was very broad and innovative concepts for new processes and materials emerged or were supported; among them rapid solidification, which led to the development of amorphous—glassy – metals; controlled solidification which led eventually to single crystal structural components such as turbine blades; and composites, especially metal matrix composites.

The 34th conference held in 1987 entitled “Innovations in Ultrahigh Strength Steel Technology focused on the problem of how to formulate and produce a steel having a tensile strength in the 2 GPa range with a fracture toughness near 100 $MPa.m^{1/2}$. Strength seems to be no great problem and as to the fracture toughness goal we seem to be more than halfway there, as this quote from a contribution by Watton, Olson, and Cohen illustrates. The finding that dispersed-phase transformation toughening shows significant technological potential for achieving such goals certainly deserves considerable attention.

Two consecutive conferences were devoted to ultrafine-grain size materials, the 15th to ceramics (Figure 34) and the 16th to metals (Figure 35). While the particle size range considered during the ceramics conference stopped at around 1,000- nm, extrapolation of many data plots clearly show that much good could come from even smaller particles, both with respect to room as well as elevated temperature properties. Peter Morgan from Cornell speculated on “Superplasticity in Ceramics?” during the forming process by pressure reaction sintering, e.g., MgO is produced by heating Mg(OH)2 under pressure – decomposition to water and MgO starts at 350 °C. At 600 °C the grain size is still only ~300 A (30 nm).

The metals conference too emphasized the need for smaller grain-size materials both for strength and ductility. Of course, it was well known that near-theoretical limit strengths could be achieved with single crystal, defect free whiskers, and it had also become clear that super plastic properties at practical strain rates require grain sizes in the micron and sub-micron range. Both conferences on fine-grain materials suggest to push on to even smaller grain sizes, which might have accelerated the development of the presently so exciting field of nanotechnology.

Other conferences (Figure 36) dealt with such diverse topics as Surfaces and Interfaces, Shock Waves, Powder Metallurgy, Block and Graft Co-Polymers, Nondestructive Testing, Risk and Failure Analysis, Surface Treatments, and many more. All enriched our understanding and contributed to answering the DoD’s needs, as well as stimulated spin-offs for the general good. Yes, the topic of the as-yet unpublished “First Sagamore Conference,” Residual Stresses, was also covered in the excellent 28th conference.

But, let me come back to the 1954/1955 beginnings (Figure 37). We are obviously not at the former Vanderbilt Camp Sagamore anymore (Figure 38). Many of your friends and colleagues were there – you might recognize some of them. Yes, it still exists, you might say it flourishes as and educational and recreational resource; you can visit, take your children and grandchildren for a week of wonderful Adirondack experiences, and you might even hold a conference some time again there. Unfortunately, in 1977 Syracuse University found it too “non profit” and decided to give the land to the State of New York, to be left forever wild, and sell the camp and immediately surrounding land. We all, who cherished the wonderful times we had there, were naturally sad and wondered how to continue the conferences (Figure 39-Figure 41). Luckily, the sponsors decided to keep the series going, preferably in a similar, somewhat secluded setting. We also liked the name Sagamore. The old Sagamore Hotel on Lake George, at Bolton Landing was a good next choice, with its “theater” as a lecture room. Since the hotel, like the SU Camp, was quite old at the time, it was somewhat adventurous to live and meet there. Eventually it went out of business, was sold and the conferences moved onto Cape Cod and now to this beautiful resort in Maryland.

And so you are ready to continue this wonderful Sagamore conference series. Hopefully for another 50 years. You might have wondered who or what Sagamore was? Most likely the reference is to James Fennimore Cooper’s *Last of the Mohicans* (Figure 42):

"Chingachgook laid aside his paddle; while Uncas and the scout urged the light vessel through crooked and intricate channels, where every foot that they advanced exposed them to the danger of some sudden rising on their progress. The eyes of the Sagamore moved warily from islet to islet, and copse to copse, as the canoe proceeded; and, when a clearer sheet of water permitted, his keen vision was bent along the bald rocks and impending forests that frowned upon the narrow strait."

The term "sagamore" was used by the American Indian Tribes of the northeastern United States to describe a lesser chief or a great man among the tribe to whom the true chief would look for wisdom and advice (Figure 43).

So, we all should keep looking for wisdom and advice with the help of many more Sagamore Conferences (Figure 44).

Thank you, congratulations and best wishes to all!

3. Slides from the Keynote Briefing of Dr. Volker Weiss

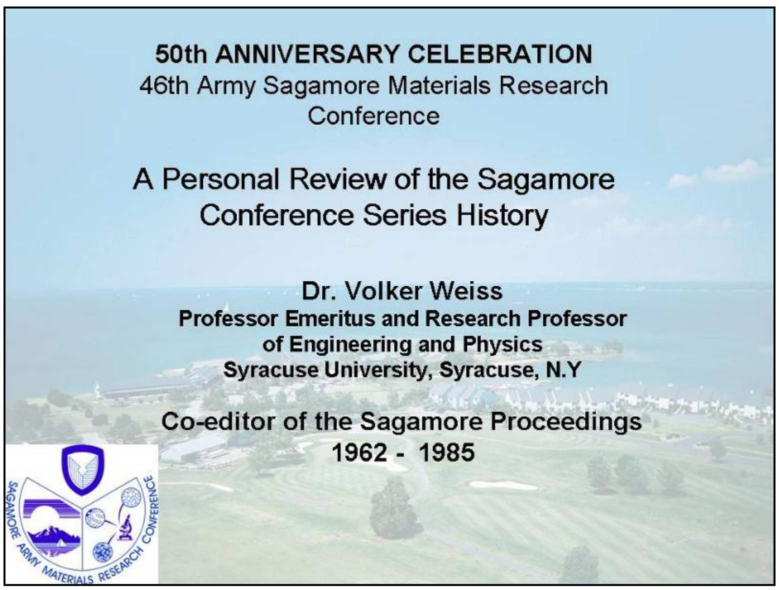


Figure 7. Dr. Volker Weiss is a distinguished and renowned scientist in the fields of engineering and physics; he provided an excellent review of the impacts of the Sagamore Conference Series in shaping current technology developments.

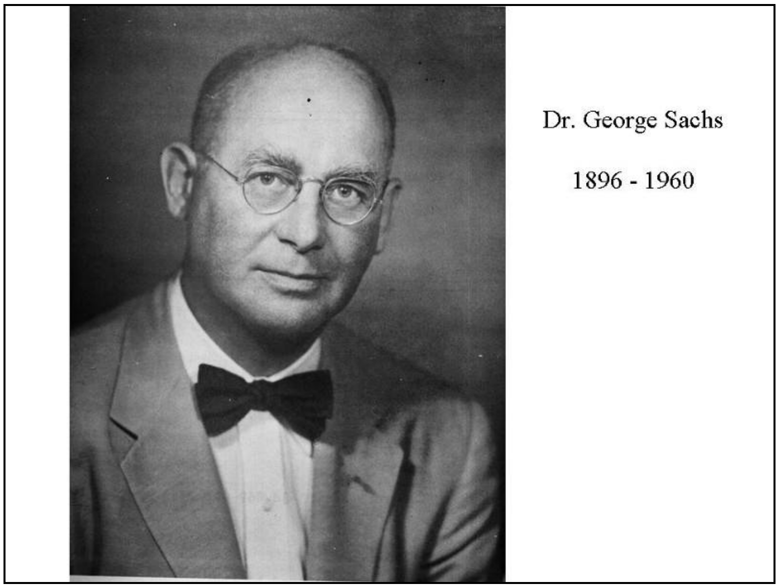


Figure 8. Dr. George Sachs, reportedly one of the pioneers for the Sagamore Research Conference Series, was an integral part of creating the footprint that is currently used to facilitate technical exchange between science and engineering in the Sagamore setting.

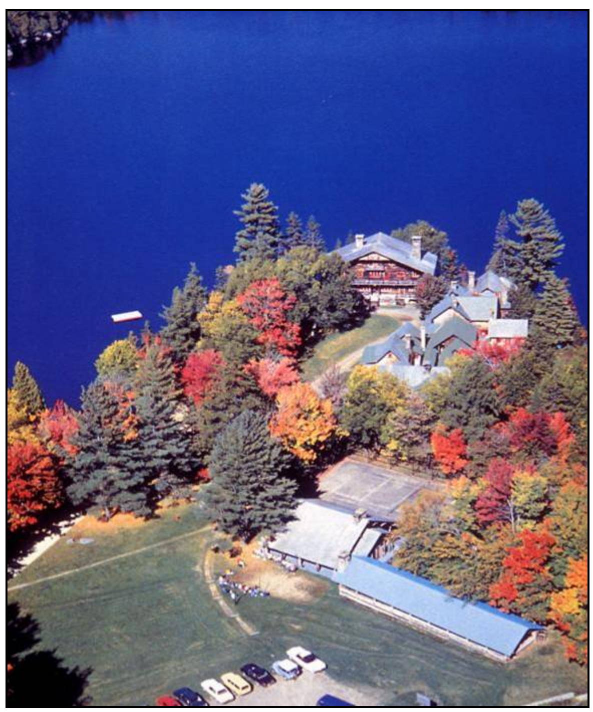


Figure 9. While the Sagamore Lodge is no longer a rustic escape that it was during the first Sagamore meetings, the memories of the Sagamore Conferences held there are unique and valued by all who participated.

Figure 10. A number of the historic photographic records shared by Dr. Weiss during his briefing resulted from a publication by Howard Kirshenbaum.

Figure 11. The Sagamore Lodge consisted of a number of buildings on the small island on the lake. Shown is the main lodge where meetings were hosted; the small space was ideal for keeping the meetings focused and intimate.

Figure 12. It was truly remote, allowing for all kinds of wildlife encounters; Dr. Weiss discusses the passing of a bear through camp one evening.

"Office and Lecture" building

Figure 13. Office and lecture building of the Sagamore Lodge in 1982.

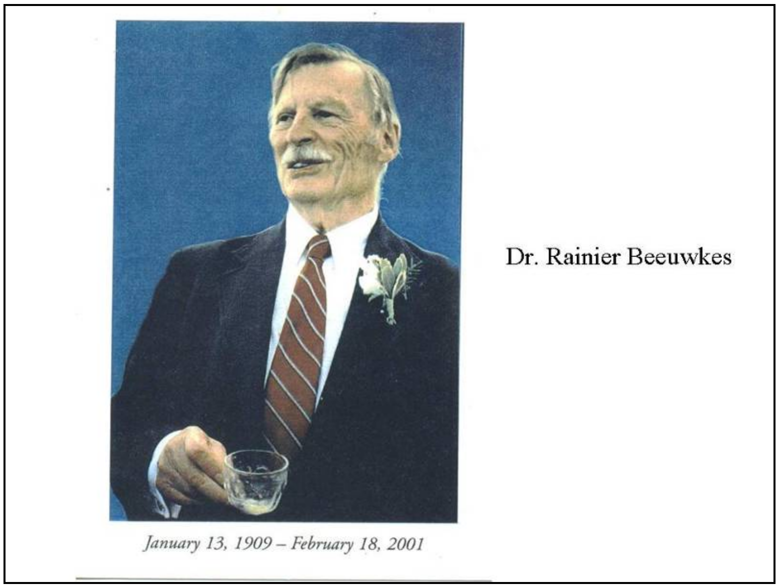


Figure 14. Dr. Rainier Beeuwkes was one of the original committee members responsible for starting the Sagamore Conference series back in 1954.

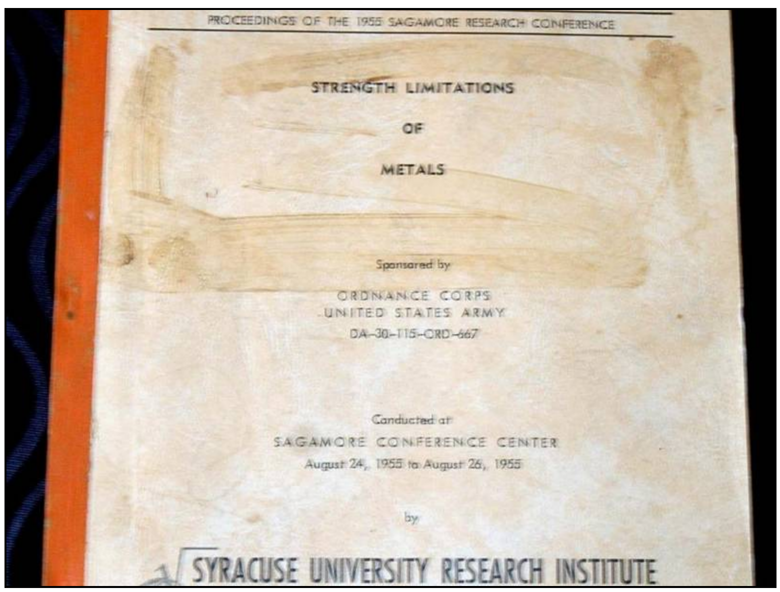


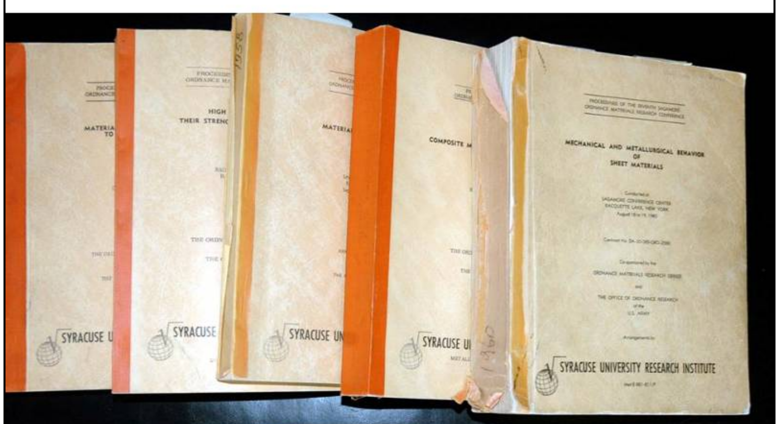
Figure 15. Although published, few people have as extensive a collection of Sagamore Proceedings as Dr. Weiss; his relationship to the publishing house as well as the conference facilitated his owning a significant library of Sagamore meeting documents.

Preface
Second Sagamore Research Conference
Strength Limitations of Metals
August 24 to August 26, 1955

This research conference was the second of an annual series devoted to a subject of primary interest to the Army Ordnance Corps. The conferences are intended to provide governmental and associated non-governmental groups with an up-to-the-minute, correlated picture of the most recent advances, of probable future developments, and of the principles involved in a particularly important, but rather narrow field of metals technology.

Lectures were presented by six representatives of the U. S. Government, six representatives of university laboratories, and six speakers from industry. A guest speaker from Great Britain, Dr. P. B. Hirsch of the Cavendish Laboratory, Cambridge, presented a lecture on "Dislocation and Strength."

Figure 16. The preface from the proceedings of the 1955 Sagamore Research Conference is an indication of the diversity of attendees at the conferences.



1956 to 1960 Conference Proceedings

Figure 17. Photographs of the proceedings documents from 1956 to 1960 from Volker Weiss' personal collection.

George Sachs, Rainier Beeuwkes, Bill Brown, W.H. Steurer and other attendees at the 1958 Sagamore Conference; Materials in Space Environment.

Figure 18. George Sachs, Rainier Beeuwkes, Bill Brown, W.H. Steurer, and other attendees take a break outside during the 1958 Sagamore Research Conference.

Erich Schmidt of the University of Vienna, Austria, at the 1958 Sagamore Conference.

Figure 19. Erich Schmidt of the University of Vienna, Austria, was a key speaker at the 1958 meeting.

Group Picture, 1960 Sagamore Conference, Mechanical and Metallurgical Behavior of Sheet Materials.

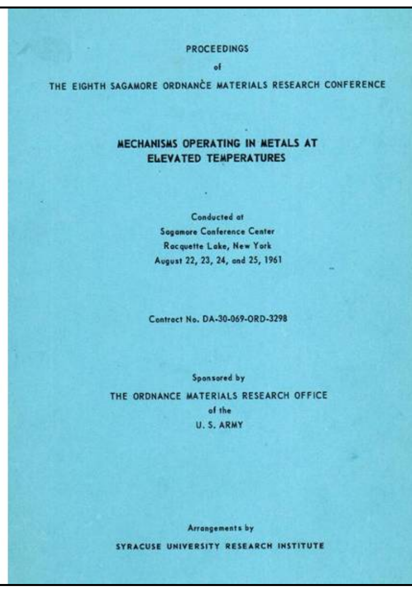
Figure 20. A group photo from the 1960 Sagamore Research Conference.

Detail of group picture, 1960 Sagamore Conference

Figure 21. An enlargement of the group photo from the 1960 Sagamore Research Conference.

George Irwin and Peter Kosting at the 1960 Sagamore Conference

Figure 22. George Irwin and Peter Kosting were chairs at the 1960 meeting.



PROCEEDINGS
of
THE EIGHTH SAGAMORE ORDNANCE MATERIALS RESEARCH CONFERENCE

MECHANISMS OPERATING IN METALS AT
ELEVATED TEMPERATURES

Conducted at
Sagamore Conference Center
Racquette Lake, New York
August 22, 23, 24, and 25, 1961

Contract No. DA-30-069-ORD-3298

Sponsored by
THE ORDNANCE MATERIALS RESEARCH OFFICE
of the
U. S. ARMY

Arrangements by
SYRACUSE UNIVERSITY RESEARCH INSTITUTE

The eighth (1961) Sagamore conference was the first one after the death of George Sachs.

A crucial test whether or not to continue the conference series.

Figure 23. The cover page from the 1961 Sagamore Research Conference; this was the first proceedings to follow the death of George Sachs.

1961 Sagamore Conference
Mechanisms Operating in Metals at Elevated Temperatures

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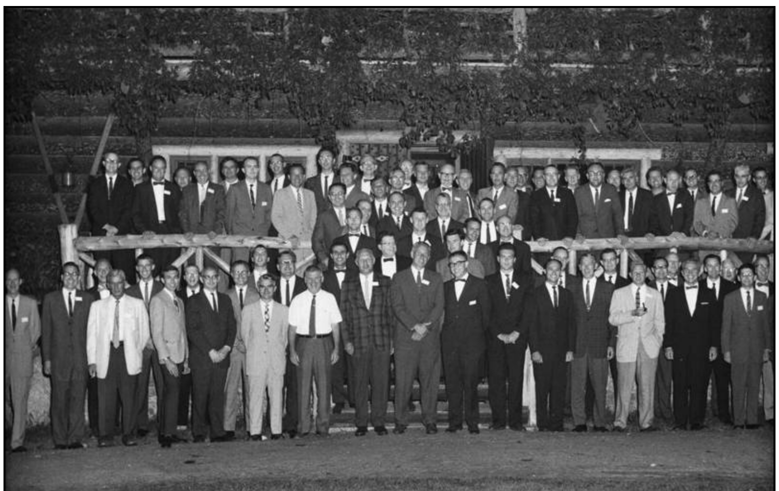
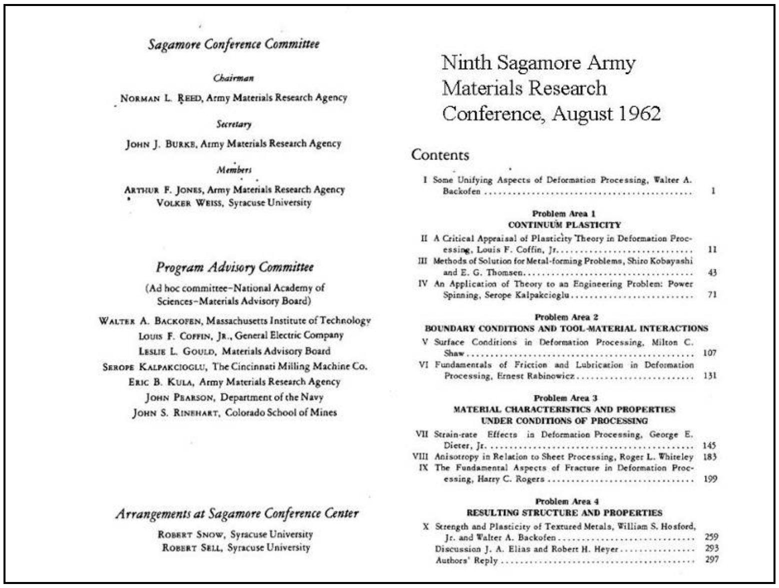
Figure 24. The content of the 1961 Sagamore Conference was focused on metals in elevated temperature environments.



Group picture of attendees of the 9th Sagamore Conference, Fundamentals of Deformation Processing, August 1962

Figure 25. In 1962, the Sagamore attendees were again photographed in front of the Sagamore Lodge.



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Secretary

JOHN J. BURKE, Army Materials Research Agency

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JOHN S. RINEHART, Colorado School of Mines

Arrangements at Sagamore Conference Center

ROBERT SNOW, Syracuse University
ROBERT SELL, Syracuse University

Ninth Sagamore Army Materials Research Conference, August 1962

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Figure 26. Copies of the organizing members and the conference content from the 9th Sagamore Conference.

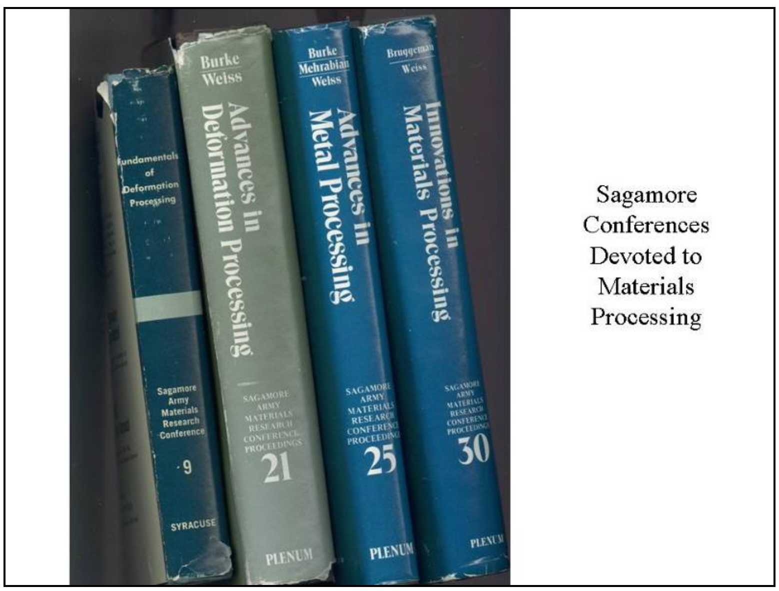


Figure 27. Materials has remained a key focus of Sagamore conferences as demonstrated by the 9th, 21st, 25th, and 30th proceedings.

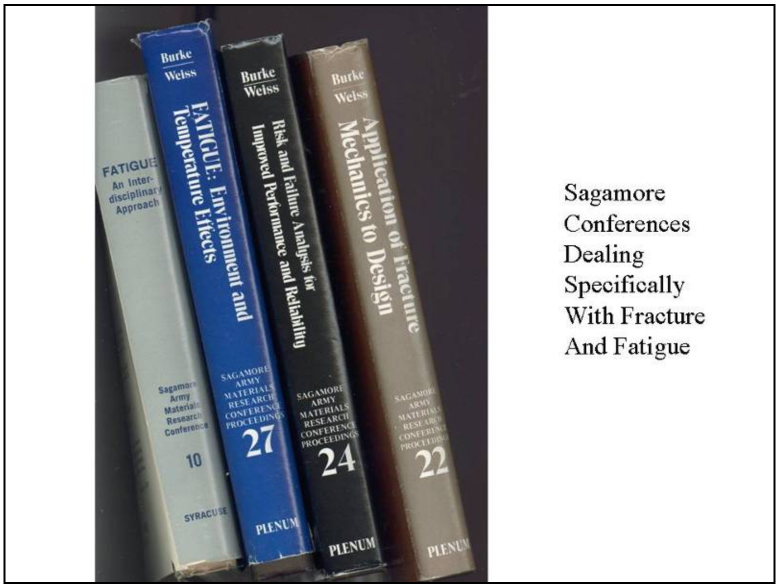
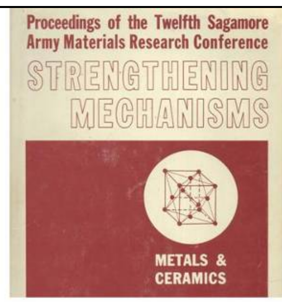


Figure 28. Fracture and fatigue is also a critical topic of concern as demonstrated by 10th, 22nd, 24th, and 27th proceedings.



One of the most interesting potential areas of investigation is that of the "spinodal" alloys in which high strength can be produced in two-phase solid solution alloy systems. In all cases investigated to date, however, even though the strength levels obtained in such materials were high, the alloys have been brittle and, hence, of limited interest or use. Additional investigations, particularly of structure, are needed to reveal the cause of the brittle behavior of these materials.

In conclusion, it should be recognized that while a great deal of progress has been made in producing high-strength materials, there is a great deal yet to be done in combining high strength with high toughness.

Figure 29. Excerpt from the 12th Sagamore conference.

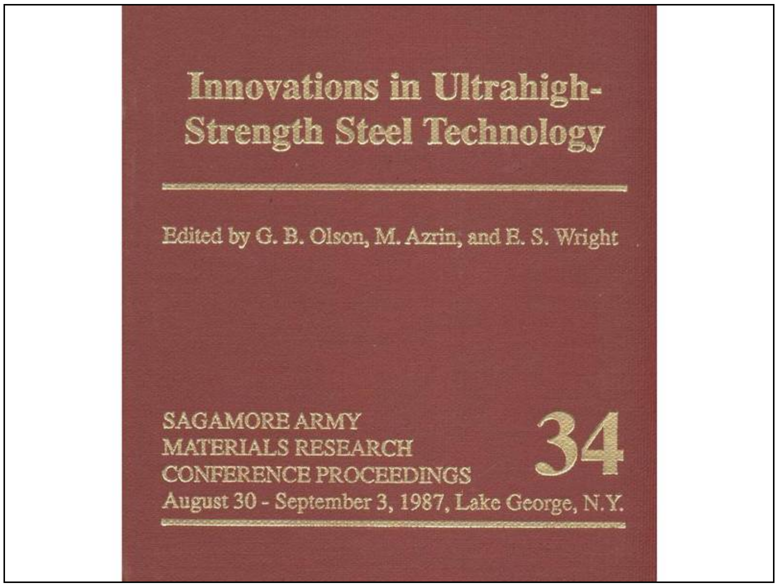
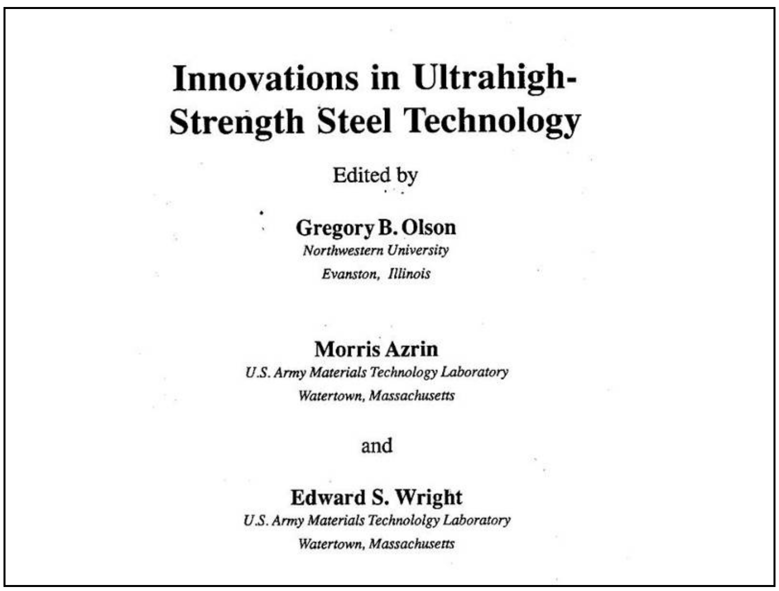


Figure 30. Cover page from the 34th Sagamore Conference.



**Innovations in Ultrahigh-
Strength Steel Technology**

Edited by

Gregory B. Olson
Northwestern University
Evanston, Illinois

Morris Azrin
U.S. Army Materials Technology Laboratory
Watertown, Massachusetts

and

Edward S. Wright
U.S. Army Materials Technololgy Laboratory
Watertown, Massachusetts

Figure 31. Steel remains a key interest area for the Army and a focus of the 1934 meeting.

34th SAGAMORE CONFERENCE COMMITTEE

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505 King Avenue
Columbus, Ohio 43201

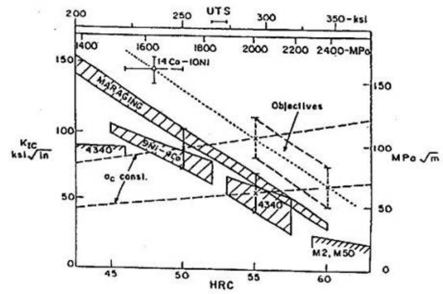

Fig. 1 Typical plane-strain fracture toughness (K_{IC}) vs. Rockwell C hardness (HRC) for commercial ultrahigh-strength steels currently employed in advanced structural applications. Upper scale shows approximate ultimate tensile strength (UTS) with indicated error limit. Strength/toughness objectives depicted allow an advance in useable strength corresponding to 5 points HRC.

Figure 32. Typical plane-strain fracture toughness versus Rockwell C hardness for commercial and high strength steels.

4. Yield and ultimate tensile strengths of 1718-1863 MPa (249-271 ksi) and 2091-2456 MPa (303-356 ksi), respectively, were achieved in spite of poor powder cleanliness.

5. Fracture toughness of heats 1 and 2 was seriously affected by cross contamination of Fe-Ni powder particles and exogenous inclusions. Heat 3, the lowest La and cleanest of the three heats, had a K_{Ic} of 65 MPa(m)$^{1/2}$ (59.2 ksi(in)$^{1/2}$) at 55 HRC which is superior to 4340 with the same hardness. The fracture mode was 100% ductile showing a significant improvement over the partial quasi-cleavage fracture typical of 4340 at these strength levels.

From John F. Watton, Gregory B. Olson and Morris Cohen,
A Novel Hydrogen-Resistant UHS Steel

Figure 33. Definitions of high strengths in steels are offered.

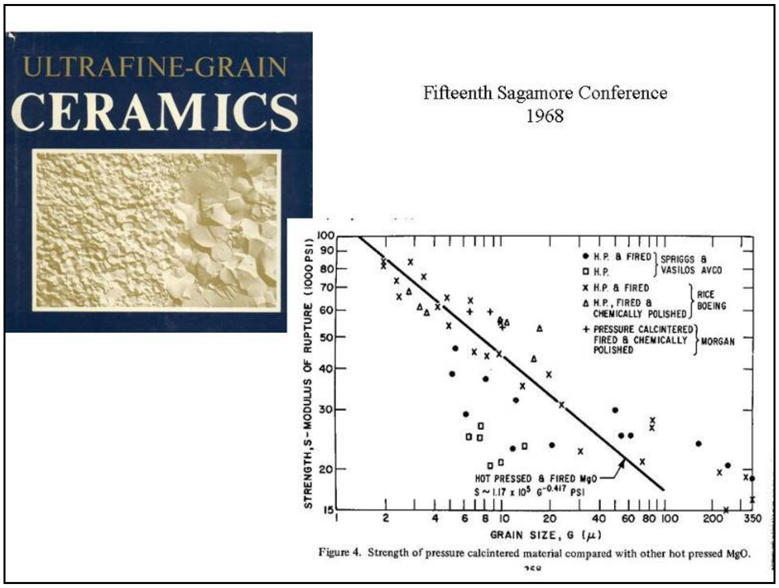

Figure 34. Ceramics has also remained a highly evolving technology with great interest to the Army as demonstrated in the 1968 conference.

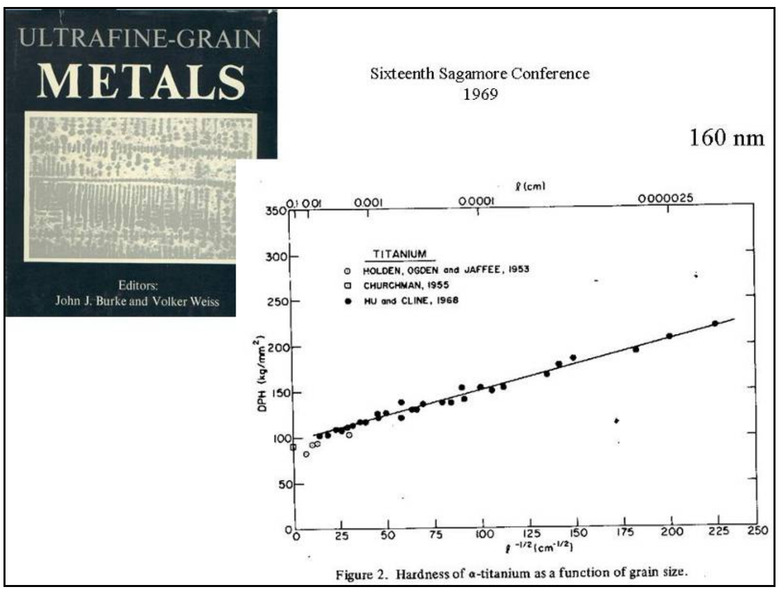

Figure 35. The control of physical properties using grain size was first discussed in 1969 at the Sagamore event.

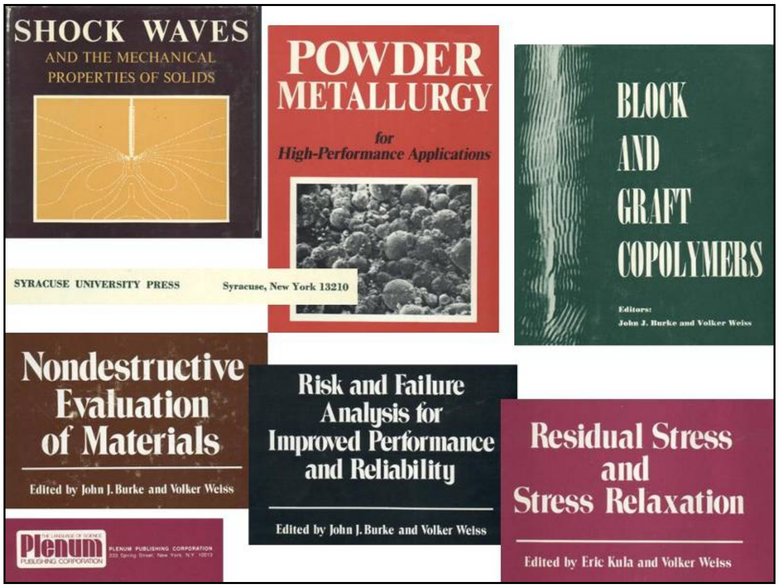

Figure 36. A range of other still important scientific topics were subjects of other Sagamore exchange meetings.

Robert F. Mehl at Sagamore

Figure 37. Robert Mehl and Volker Weiss (right) and some colleagues at a 1970 Sagamore meeting.

Figure 38. Various snapshots representing the conference events with early attendees at Sagamore Lodge.

Figure 39. The dining room at the Sagamore Lodge.

Figure 40. One of the breakout rooms used during Sagamore events at the lodge.

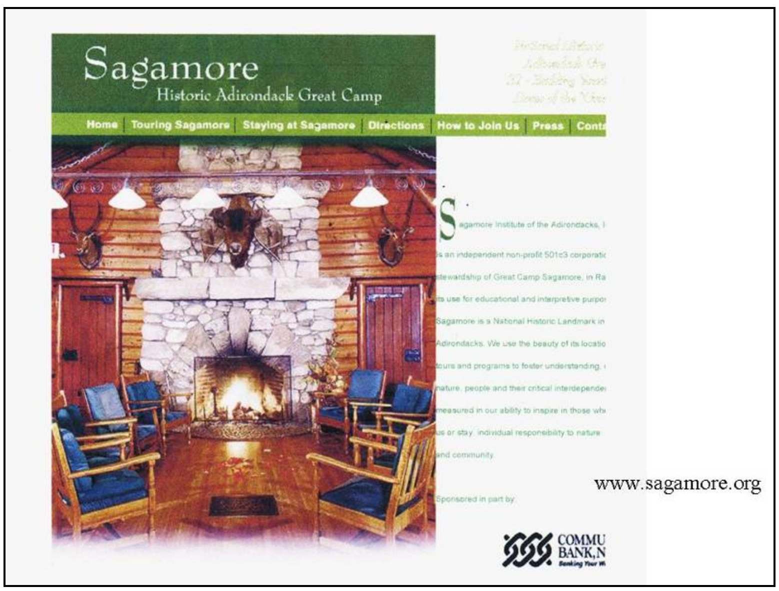

Figure 41. Fireplace room in the cabins at Sagamore Lodge.

Chingachgook laid aside his paddle; while Uncas and the scout urged the light vessel through crooked and intricate channels, where every foot that they advanced exposed them to the danger of some sudden rising on their progress. The eyes of the Sagamore moved warily from islet to islet, and copse to copse, as the canoe proceeded; and, when a clearer sheet of water permitted, his keen vision was bent along the bald rocks and impending forests that frowned upon the narrow strait.

Figure 42. Quotation from *Last of the Mohicans*.

The term "sagamore" was used by the American Indian Tribes of the northeastern United States to describe a lesser chief or a great man among the tribe to whom the true chief would look for wisdom and advice.

Figure 43. Historic definition of the term Sagamore.

Figure 44. A personal blessing from Volker Weiss for continued success in Sagamore Research Conferences.

4. Conference Agenda

Session I. Plenary Session on Applications and Needs for Transparent Materials Technology

Chairs: Dr. James M. Sands and Dr. James W. McCauley, ARL, APG, MD

Briefing Title	Presenting Author
Welcome and Opening Remarks	Dr. Allen Grum Associate Director for Science and Technology (S&T), ARL
The Impact of Research on Soldier Protection	Ms. Jill Smith Director, WMRD, ARL
The History and Purpose of the Army Sagamore Materials Conference	Dr. James McCauley ST, ARL
AoA for TWVs (Add-on-Armor for Tactical Wheeled Vehicles) and TWV Armoring Needs for the Way Forward	Major Daniel Rusin Military Dep, Armor Mech Branch, ARL
The Challenges of On-The-Move Satellite Communications	Mr. Louis Coryell Team Leader, Satellite Communication (SATCOM) Antenna Research and Development (R&D), Communications-Electronics Research Development and Engineering Center (CERDEC) Space & Terrestrial Communications Directorate
Polycrystalline Materials for Laser Applications	Dr. Richard Gentilman Senior Engineering Manager, Raytheon Company
Advances and Needs in Multi-Spectral Transparent Materials Technology	Dr. Daniel Harris Senior Scientist, Naval Air Systems Command

Session II. Transparent Electromagnetic Systems

Chair: Dr. Daniel Harris

Briefing Title	Presenting Author
Tri-mode Seeker Dome Considerations	Dr. James Kirsch Research Optical Engineer, U.S. Army Aviation & Missile Research, Development, and Engineering Center (AMRDEC)
Missile Systems and Guidance Requirements	Dr. Randy Tustison Manager of Materials Engineering, Raytheon Integrated Defense Systems
Material Requirements for Large Area Windows	Mr. Joel Askinazi Chief Engineer, Adv. Window Dev., Goodrich Electro-Optical Systems

Session III. Ceramic Processing and Industrial Panel

Chair: Dr. Dennis Viechnicki

Briefing Title	Presenting Author
Advances in Transparent Polycrystalline Oxide Windows	Dr. William Rhodes Rhodes Consulting
INDUSTRIAL PANEL 1. Surmet, Dr. Suri Sastri 2. Crystal Systems, Dr. Chandra Khattak 3. MSI, Dr. Les Bowen 4. TA&T, Dr. Larry Fehrenbacher 5. CeraNova, Dr. Marina Pascucci	

Session IV. Multifunctional Transparent Materials

Chair: Dr. James McCauley, ARL, APG, MD

Briefing Title	Presenting Author
Transparent Electrooptic Ceramics: A Technology Review	Dr. Gene Haertling Professor Emeritus, Clemson University
Novel TCOs for Next Generation Organic Solar Cells and Electronics	Dr. David Ginley Group Manager, National Renewable Energy Lab
Multifunctional Transparent Systems	Dr. Richard Riman Professor, Rutgers University
High Strength Glass, Polymers and Coatings for Transparencies	Dr. Amar Mishra Associate Director, Aerospace and Specialty Materials R&D, PPG Industries

Session V. Transparent Armor: Needs and Future Challenges

Chair: Dr. Parimal Patel, ARL, APG, MD

Briefing Title	Presenting Author
Ground Vehicle Transparency Requirements	Mr. Gregory Wolfe Survivability Engineer, U.S. Army Research Development and Engineering Command (RDECOM)-Tank and Automotive Research, Development and Engineering Center (TARDEC)
Aviation Issues	Mr. Robert Hood Team Leader, Subsystems, Aviation Applied Technology Directorate
Failures in the Field Environment	Ms. Lisa Prokurat Franks Program Manager, U.S. Army TARDEC

Session VI. Transparent Armor: Mechanics and Materials

Chair: Dr. James M. Sands

Briefing Title	Presenting Author
Failure Waves in Glass and Their Possible Roles in Determining Penetration Resistance	Dr. Stephan Bless Senior Research Scientist, Institute for Advanced Technology at The University of Texas at Austin
Preparation, Properties and Uses for Bulk, Alumina-based Glasses	Dr. Berkan Endres Senior Research Specialist, 3M Company
Design of Residual Stresses in Transparent Materials Using Residual Stresses	Dr. David Green Professor of Materials Science, The Pennsylvania State University
Large Compression Depth Chemically Strengthened Glass	Dr. Arun Varshneya Prof. of Glass Science & Engineering, Alfred University
Fabrication and Characterization of Transparent Polycrystalline Silicon Nitride Ceramic	Dr. Soo Wohn Lee Professor, Sun Moon University
Advanced Aliphatic Polyurethane Resins for High Durability and Superior Ballistic Performance Ballistic Glass	Dr. Francisco Folgar Director, INTER Materials, LLC
Transparent Alumina	Dr. Theo Kop Senior Scientist, Philips Research
New Routes to Fabricating Transparent Armors and Polymer Glasses	Dr. Alan Lesser Professor, University of Massachusetts
Electrospun Nanofiber Reinforcement of Transparent Polymer Materials	Dr. Joseph Deitzel Research Associate, University of Delaware
Ceramic/Polymer Hybrid Systems for Improved Ballistics	Dr. Kevin Yu Director, Holographic Systems, Physical Optics Corporation
Round Table/Question and Answers Session	

Banquet Session. Keynote Address

Briefing Title	Presenting Author
Keynote Speaker	Dr. Volker Weiss Emeritus Professor of Engineering and Physics, Syracuse University

Session VII. Polycrystalline Materials for Laser Applications

Chair: Mr. Gary Gilde

Briefing Title	Presenting Author
State-of-the-art of Polycrystalline Oxide Laser Gain Materials	Dr. Gregory Quarles Director of Research and Development, VLOC, Inc.
Sintering of Polycrystalline YAG for Laser Host	Dr. Gary Messing Head, Department of Materials, Pennsylvania State University
Review of ARL's Effort on Diode-Pumped Ceramic Lasers	Dr. Mark Dubinskiy Team Leader, High Energy Laser, ARL
Polycrystalline YAG: Laser Host Material	Dr. HeeDong Lee Materials Research Scientist, UES, Inc.
High Purity, Unagglomerated Nanopowders for Implementation in High Energy Laser Systems	Dr. Todd Polley Vice President of Electronics & Optics, nGimat Company
Agiltron Laser Ceramics Development	Dr. King Wang Principal Scientist, Agiltron, Inc.
Issues and Opportunities for Using Custom Formulated Nanopowders to Prepare Nanostructured Transparent Ceramics	Dr. Anthony Sutorik Lab Director, Nanocerox, Inc.

5. Summary Abstracts of Briefings by Session

5.1 Session I: Applications and Needs for Transparent Materials Technology

Chairs: Dr. James Sands and Dr. James McCauley, ARL, APG, MD

The reports in this session are part of the keynote briefings that set the tone for the week of meetings. As such, the presentations offered in this section are included in their entirety as part of this publication and are located in section 7.

5.2 Session II: Transparent Electromagnetic Systems

Chair: Dr. Daniel Harris

5.2.1 Tri-Mode Dome Considerations

James Kirsch, AMRDEC

The dome or window on a sensor suite seems, at first glance, to be a relatively low tech item. In reality, it can be one of the most costly items in the system. The choice of materials is highly dependent on the sensor, the anticipated operating conditions, and other requirements such as electromagnetic interference or radar cross section issues. The situation is further complicated when multiple sensor bands are used, such as in a tri-mode seeker containing semi-active laser, midwave infrared, and millimeter sensors all using a common aperture. The dome issues for this type of system require innovative new solutions.

5.2.2 Trends in Infrared Missile Dome Technology

R.W. Tustison, Raytheon Integrated Defense Systems

It has been 50 years or so since the first infrared guided missile, AIM9A, was fired. In many ways this set in motion the search for the ideal infrared transparent, durable missile dome material. By the late 1970s, the materials which we are using today were either in production or under development. The list of materials options has not changed greatly in the intervening years. This presentation will review this evolution and will examine engineering solutions, which attempt to compensate for the shortcomings of available infrared dome materials.

5.2.3 Material Requirements for Large Area Windows

Joel Askinazi, Goodrich Electro-Optical Systems, 100 Wooster Heights Road, Danbury, CT 06810

Emerging needs for optical sensor windows are dictating new optical material requirements. These include the need for much larger physical aperture dimensions, improved optical performance, and material property uniformity along with reduced lifecycle cost.

The key objective of this paper is to communicate the general class of these emerging optical window requirements and to contrast them with those for other applications, such as laser windows and transparent armor. The goal is to provide material suppliers with a set of requirements to guide their development efforts.

5.3 Session III: Ceramic Processing and Industrial Panel

Chair: Dr. Dennis Viechnicki

5.3.1 Advances in Transparent Polycrystalline Oxide Windows

William H. Rhodes, consultant

Significant advances have been made in oxide windows in the last five years. These include improved powders, consolidation methods, and the introduction of transparent anisotropic polycrystalline oxides. The various methods for producing nanopowders are reviewed. Noteworthy, are trends in pressure assisted consolidation and the remarkable sintering of laser quality oxides. Anisotropic materials have been sinter/hot isostatic pressed (HIPed) to transparency. The theory explaining this finding is reviewed, and theory is compared with the experimental optical properties of polycrystalline alumina (PCA).

5.4 Session IV: Multifunctional Transparent Materials

Chair: Dr. James McCauley, ARL, APG, MD

5.4.1 Transparent Electro-optic Ceramics: A Technology Review

Gene Haertling, consultant

The technology of electro-optic ceramics is reviewed in regard to general principles of applicability for ceramics; specific materials and compositions; successful processing techniques; properties and phenomena unique to polycrystalline ceramics; and time-proven, specific applications with special emphasis on more recent developments. Although the polarized lead zirconium titanates (PLZTs) still remain the standard of the industry for transparency and ease of manufacture, other materials such as Lanthanum (La)-doped lead magnesium niobate-lead titanate (PMN-PT) and lead zinc niobate-lead titanate (PZN-PT) are now serious contenders. Newly developed applications for electro-optic ceramics include variable optical attenuators, filters, switches, and special polarization controllers.

5.4.2 TCOs for Next Generation Organic Solar Cells and Electronics

David Ginley, National Renewable Energy Laboratory, Golden, CO 80401; Matthew White, University of Colorado Boulder, Boulder, CO 80309; and Dana Olson, Maikel Van Hest, Matthew Taylor, Charles Teplin, Dennis Readey, Mathew Dabney, and John Perkins, Colorado School of Mines, Golden, CO 80401

As a next generation of quantum dot, organic, and bio-inspired opto-electronic devices evolve, the needs for transparent conducting oxides (TCOs) are beginning to change dramatically. Many of these devices will involve the integration of these elements in a complex composite, potentially demanding non-planar TCOs on the nanoscale. We will report here on the development of new TCO materials and illustrate the importance of the broadening requirements with some device examples. In addition, for organic and bio-based systems, low process temperatures are critical, leading to the need to be able deposit materials at room temperature with good properties. We discuss recent results on the amorphous indium (In)-zinc (Zn)-oxygen (O) system, which appears ideal for these systems and flexible substrates, that can be deposited at room temperature to form remarkably smooth (10 Å rms) films with excellent conductivity and transparency (3000 S/cm, 85% transparent in the visible), and exceptional thermal stability (>400 °C) over a wide composition range. For organics and biomaterials, due to low mobilities and short exciton diffusion lengths, many of these new device types must be structured on the nanoscale. We will discuss how this can be accomplished with nanocarpets of solution grown

ZnO or TiO_2 nanofibers or nanotubes or with novel composites with TCO nanoparticles. We will discuss new device results on incorporating these nanostructured oxides into organic photovoltaics and the key limiting factors observed thus far.

We would like to acknowledge the support of Defense Advanced Research Projects Agency (DARPA) and the Department of Energy National Center for Photovoltaics.

5.4.3 Transparent Multifunctional Armor (TMA) Materials

Richard E. Riman, Department of Materials Engineering, 607 Taylor Road, Rutgers, The State University of New Jersey, NJ

TMA materials can offer protection in land-, sea- and air-based applications. The large surface areas required by such armor provide an opportunity for implementation of other types of devices that can give our Soldiers a tactical advantage. The foundation of our TMA concept is a glass-polymer laminate manufactured by Dupont, which offers significant structural materials properties and weight advantages over any glass-polymer laminates currently manufactured. Since these laminates are not now used by the military, an important opportunity exists to make a significant impact on transparent armor technology. These improvements in properties and weight are based on recent advances in ionomer engineering, which can be further enhanced by optimizing their molecular characteristics. Further improvements may also be realized when ceramic materials other than glass are considered, such as aluminum oxynitride (AlON). A variety of additional functional capabilities can be engineered into the polymer phase. At Rutgers, transparent functional composites have been either demonstrated or are in development with functionalities such as thermal energy management, energy storage, optical signature, signature morphing, flame retardancy, and rapid attenuation from energy directed weapons. All of these functions can be incorporated in a component multilayer approach where polymer, glass, and ceramic layers can be tailored to provide numerous functionalities. The purpose of this talk is to discuss developed functionalities (e.g., optical signature) and define and nucleate new programs and teams to address military needs for TMAs.

5.4.4 High Strength Glass, Polymers, and Coatings for Transparencies

Amar Mishra, PPG Industries, Inc., 4325 Rosanna Dr., Allison Park, PA 15101

The performance requirements for transparencies continue to be raised due to requirements in the market place. PPG, through its continuing research and development, has been a leader in developing transparency systems for both military and commercial applications. The transparencies are composites of glass, plastics, interlayers, and sealants with a variety of coatings to provide additional functionalities. New developments of material systems that will further enhance transparency and ballistic performance will be presented. Finally, PPG’s ongoing involvement with the military will be reviewed.

5.5 Session V: Transparent Armor: Needs and Future Challenges

Chair: Dr. Parimal Patel

5.5.1 Transparent Armor Needs for Ground Vehicles

Gregory Wolfe, U.S. Army TARDEC/RDECOM, Warren, MI

This presentation provides a snapshot of the U.S. Army's efforts in design and development of add-on-armor (AoA) kits for Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF). A summary of AoA kits in production is provided with images depicting transparency uses. Mortality data is provided to develop an understanding of the threats facing the vehicles. Requirements for transparent armor are detailed, beginning with a discussion of the primary threats to ground vehicles and the resulting ballistic performance needs, including multi-hit performance, protection level specification, optical performance, durability issues, defrost/defog performance, and emerging needs.

5.5.2 Aviation Issues

Robert C. Hood, Team Leader, Subsystems Platform Technology Division, Aviation Applied Technology Directorate, AMRDEC, Ft. Eustis, VA

Army aviation platforms make extensive use of transparencies as windshields, cockpit/cabin windows, blast shields, sensor apertures, laser range finders/ designators, and other applications. While optical properties are obviously significant, system weight is of critical importance for use on an aircraft and is often overlooked by the designers. Additionally, issues relating to operational environment are often neglected. For example, transparencies in use today are typically designed to provide tolerable system weight but little else in terms of performance. Ideally, we would like to have transparencies, and all other aircraft systems for that matter, be not only lightweight but durable, maintainable, and ballistically tolerant under all operating environmental conditions anywhere in the world where our forces may be deployed. In addition to these goals, transparencies that offer ballistic protection and/or have self healing properties are desired.

5.5.3 Transparent Armor Cost Benefit Study

Lisa Prokurat Franks, U.S. Army TARDEC/RDECOM, Warren, MI

Dave Holm and Richard Barnak, U.S. Army Tank-automotive and Armaments Command (TACOM) Cost & Systems Analysis Directorate, Warren, MI

This presentation outlines the background, proposed methodology, and time frame for a new study to determine when advanced materials for transparent armor may become cost effective for tactical vehicles. The study will be conducted concurrently with basic research by GE Global Research investigating the processing, analysis, and production of transparent nanoceramics.

Current demand for replacement windshields and windows for the Up Armored High Mobility Multi-purpose Wheeled Vehicle (HMMWV) and causes of failure will be presented. A methodology and time frame to find the break-even cost point will be proposed.

5.6 Session VI: Transparent Armor: Mechanics and Materials

Chair: Dr. James Sands

5.6.1 Failure Waves in Glass and Their Possible Roles in Determining Penetration Resistance

Stephan J. Bless, Institute for Advanced Technology, University of Texas at Austin, TX

High speed impacts on glass excite a failure mode not observed in conventional indentation and impact loading—formation of a failure wave (FW). Properties of FW have been investigated in plate impact experiments, in which propagation velocity and strength behind the wave “front” have been determined. The FW “front” has been shown to be a transition from intact to comminuted material. Models for FWs fall into two types: crack diffusion or delayed fracture. Ceramic armor in general and glass armor in particular, may be categorized as “thin” or “thick.” FWs affect both types, first by influencing whether or not dwell occurs, and second by limiting the duration of the dwell phase.

5.6.2 Preparation, Properties, and Applications for Bulk Alumina-Based Glasses

B. Endres, A. Rosenflanz, T. Anderson, B. Richards, 3M Company, St. Paul, MN

Alumina (Al_2O_3) is often regarded as a network former in conventional silicate glasses; however, it cannot be obtained as a bulk glass. Glasses comprising continuously linked (AlO_x) polyhedra have been prepared in only a few systems under very rapid quenching, and only in dimensions less than a few millimetres. Yet, it is desirable to prepare bulk, or monolithic, alumina-rich glasses, with the prospect of superior mechanical, chemical, and optical properties. Dense nanocrystalline alumina is also attractive since it exhibits translucency, superplasticity, and the highest hardness of any oxide ceramic. Unfortunately, the retention of nanosized grains during pressureless sintering is challenging because of the concurrent nature of densification and grain growth and so far has been achieved only in few ceramic systems. Sintering of nanocrystalline alumina requires impractically high applied pressure (e.g., >1 GPa). Here we report a novel process for preparing very high-alumina glasses and nanoscale glass-ceramics. Fully dense bulk articles in net shape are obtained through viscous sintering of glass microbeads. Additional heat treatment of the consolidated glasses leads to fully crystallized transparent glass converted ceramic bodies with the similar hardness to alumina. The properties and potential applications of resulting aluminate glass microbeads, bulk glasses, and nanocrystalline ceramics will also be discussed.

5.6.3 Design of Residual Stresses in Transparent Materials Using Residual Stresses

David J. Green, Department of Materials Science and Engineering. The Pennsylvania State University, University Park, PA 16802

In transparent materials, such as glass, it is difficult to identify toughening and strengthening mechanisms because there is often no microstructure to manipulate. In these cases, residual surface compression has been developed as the strengthening method, e.g., by thermal tempering or chemical strengthening, especially in situations where materials fail exclusively from surface flaws. This approach can lead to other important benefits, notably improvements in the resistance to stress corrosion and contact damage. Although very successful, these approaches still lead to catastrophic failure and increased strength variability.

Recently, it has been shown that engineering the shape of the surface profile produced by chemical strengthening can lead to other improvements. With these engineered stress profile (ESP) glasses, strengths can be increased while decreasing strength variability. In ESP glasses, surface cracks are arrested and this can lead to multiple cracking as a “warning” of failure. The phenomenon of multiple cracking implies that the surfaces of these glasses can be damaged without any loss of strength and this has been confirmed experimentally. An overview of the processing techniques used to produce ESP glasses, the relationship of the processing to the final stress profile, and the resultant mechanical properties will be reviewed.

5.6.4 Faster and Deeper Chemical Strengthening of Glass for Security Applications

Arun K. Varshneya, William C. LaCourse, Saxon Glass Technologies, Inc., Alfred, NY; and I. Spinelli, NY State College of Ceramics at Alfred University, Alfred, NY

Chemical strengthening of two glass families has been studied. One of them, a hitherto “undiscovered but commercially available” lithium aluminosilicate glass has been found to develop as much as 600–1000 microns deep compressive stress profile with as little as 8 h to 1 day of treatment. Surface compression achieved is ~1000 MPa. The compression remains above 200 MPa even at ~300 microns depth. Such profiles are much deeper and much faster than in any glass study published. Applications could (1) tailor-make the protection level exceeding that provided by the large compression case depth of thermally tempered glass without the risk of dicing, or (2) obtain strong but frangible glass products.

A second family, common soda-lime-silicate (SLS) float glass, has been studied using a rapid chemical strengthening process. Case depths of more than 80 microns are easily obtained with a combination of salt spray and thermal soak treatment over as little as 4 h. These depths are equivalent to those obtained after 4–6 days of conventional KNO_3 ion-exchange. Maximum surface compressive stresses are lower than those describe above (~300 MPa), but the process is much less expensive since commercial SLS glass can be employed. Greater depths and higher maximum surface compression can be obtained with process modifications.

5.6.5 Fabrication and Characterization of Transparent Polycrystalline Silicon Nitride Ceramic

Soo Wohn Lee, Department of Materials Engineering, Sun Moon University, Asan, Chung Nam 336-708, Korea; Rak Joo Sung, Sang Woo Kim, Nano-Materials Research Center, Korea Institute of Science and Technology, Seoul 136-791, Korea; and Takafumi Kusunose, Tohru Sekino, The Institute of Scientific and Industrial Research, Osaka University, Ibaraki, Osaka 562-0047, Japan

Compared to single crystals, sintered polycrystalline ceramics bodies have more complicated microstructures that consist of grains, grain boundaries, secondary phases, and pores. These structures greatly influenced physical and mechanical properties.

Densification for the polycrystalline silicon nitride requires different kind of the sintering additives. This utilization of different sintering aids may change mechanical and thermal properties of hot-pressed Si_3N_4 markedly. Amount of composition of the additives are not only of decisive influence on the sintering parameters (temperature, pressure, time, atmosphere), but also on the resulting phase relations and microstructures, which emphatically determine many physical properties of silicon nitride (Si_3N_4) ceramics. In this study, optical and mechanical properties of hot-pressed Si_3N_4 were investigated with changing the amount of magnesium oxide (MgO) and aluminum nitride (AlN) as the sintering aids.

Transparent polycrystalline Si_3N_4 was successfully fabricated by hot press sintering method at 1850 and 1900 °C with adding 3 wt.% MgO and 9 wt.% AlN as sintering aids. To decrease the pores and defects of polycrystalline Si_3N_4, we tried to carry out the heat-treatment at 1500 °C for 10 h in N_2 atmosphere. Transmittance increased after the heat-treatment at 1500° C for 10 h in N_2 atmosphere. The maximum transmittance after heat-treatment, 70%, is observed in the infrared region of the wavelength of 2,500 nm.

5.6.6 Advanced Optical Aliphatic Polyurethane Resins for High Durability and Superior Ballistic Performance Ballistic Glass

Dr. Francisco Folgar, President, INTER Materials, LLC, 623 Muirfield Court, Richmond, VA 23236

Advanced optical aliphatic polyurethane (PU) resins have been developed for manufacturing laminated ballistic resistant glass that are lighter and more durable than commercially available ballistic glass. The newly developed optical aliphatic PU resins have very high adhesion strength to polycarbonate and acrylic and excellent optical quality. They generate lower thermal stresses by using low processing temperatures during glass lamination. This paper discusses the properties of the new aliphatic PU resins that can increase the durability of laminated ballistic glass, increase the glass ballistic performance, and reduce its weight.

5.6.7 Transparent Alumina

R. Apetz, M.P.B. van Bruggen and T.A. Kop, Philips Research Eindhoven, The Netherlands

A model based on classical light scattering theory has been developed to describe the light transmission properties of fine-grained polycrystalline ceramics consisting of birefringent crystals. This model extends light transmission models that rely on geometrical optics, which are only valid for coarse-grained microstructures. We verify our model by measuring the light transmission properties of fully dense (>99.99%) PCA with mean grain sizes ranging from 60 μm down to 0.3 μm. The remarkable transparency of fine-grained PCA, as well as the angular distribution of the small fraction of scattered light, is well explained by the model.

5.6.8 New Routes to Fabricating Transparent Armors and Polymer Glasses

Alan Lesser, Polymer Science & Engineering Department, University of Massachusetts, Amherst, MA 01003

This presentation starts by identifying what properties and architectures are important in ballistic protective and damage tolerant glass. Next, current methods for fabricating glasses with high modulus, strength, and toughness are then discussed. Impact modification at the micron, nano, and molecular scales are discussed. Alternate routes to fabricate laminated architectures using supercritical carbon dioxide are then discussed and initial results are presented on their mechanical and optical properties.

5.6.9 Electrospun Nanofiber Reinforcement of Transparent Polymer Materials

J.M. Deitzel, C. Krauthauser, D. O'Brien, University of Delaware, Center for Composite Materials, Newark, DE

We propose a novel approach to increasing the impact properties of thermoset and thermoplastic transparent polymer resins by reinforcing these resins with high performance polymer nanofibers and/or elastomeric nanofibers. The advantages of using nanofibers for reinforcement are twofold. First, the small diameter (~100nm) of the fibers is well below the diffraction limit of visible light (ν=400-700 nm), therefore nanofibers dispersed in a transparent medium should not impinge significantly on the transmission of light in the visible range (Bergshoef and Vancso, 1999). Second, nanofiber textiles have orders of magnitude greater specific surface area than conventional fabrics, due to the small fiber diameter. The greater surface area will provide more interaction between the resin and reinforcing fiber, improving mechanical properties and potentially attenuating crack propagation. Furthermore, incorporation of a continuous network of conductive or optically active electrospun fibers can further increase the functionality of the transparent composite material, in terms of sensors, shielding, and dissipation of static charge. This presentation will introduce the basic concepts of electrospinning process; discuss the issues involved with scale-up of the process in regards to materials of interest; and present initial results for optical and mechanical testing of polymethylmethacrylate (PMMA)/electrospun fiber composites.

5.6.10 Ceramic/Polymer Hybrid Systems for Improved Ballistics

Kevin Yu, Physical Optics Corporation (POC), 20600 Gramercy Place, Building 100, Torrance, CA 90501-1821

POC is developing a new lightweight and flexible Organically Modified Sol-gel (ORMSOL) nanocomposite material to address the U.S. Army need for an innovative lightweight optically clear polymer armor. This nanocomposite material is based on unique integration of inorganic (sol-gel) and organic (polymer) material through three-dimensional crosslinking, which makes them stronger than either of them separately. Thus far, POC has developed and fabricated ORMSOL samples with the required optical, mechanical, and thermal properties. We are in this first phase of the Small Business Innovation Research (SBIR) project and have successfully demonstrated that ORMSOL has strong potential to meet U.S. Army needs.

5.7 Session VII: Polycrystalline Materials for Laser Applications

Chair: Mr. Gary Gilde

5.7.1 State-of-the-Art of Polycrystalline Oxide Laser Gain Materials

Gregory J. Quarles, Director of Research, VLOC Incorporated, subsidiary of II-VI Incorporated

This presentation will focus upon the optical, thermo-optical, and mechanical characterizations and comparisons of polycrystalline yttrium aluminum garnet (YAG) ($Y_3Al_5O_{12}$,,) and single crystal YAG. The thrust of this research is aimed at providing the laser engineering community with an unbiased and complete set of data from which designs and decisions can be made regarding the stability, availability, and efficiency of these materials for use in next-generation high-power solid state lasers (HPSSL). This research has been a team effort, with federal laboratories, universities, and private industry participating. Initial data indicates that the quality of current polycrystalline YAG is equivalent, if not superior, in some parameters, as compared to single crystalline YAG utilized for HPSSL designs.

5.7.2 Sintering of Polycrystalline Nd-YAG for Laser Hosts

Gary Messing, Sang-Ho Lee, Sujarinee Kochawattana, Kwadwo Appiagyei, Michael Ruffin, Department of Materials Science and Engineering and Materials Research Institute, The Pennsylvania State University, University Park, PA 16802; and John Dumm, II-VI Incorporated, Saxonburg, PA 16056

Transparent polycrystal neodymium yttrium aluminum garnet (Nd:YAG) ($Nd_{3x}Y_{3-3x}Al_5O_{12}$) can be produced from powders synthesized by a variety of different techniques using conventional ceramic processing method. We will discuss how the quality of the powders, features of the forming methods, and sintering conditions influence the attainment of transparent ceramics. Data from our own experience with reactive sintering will be discussed.

5.7.3 Diode-Pumped Ceramic Lasers

M. Dubinskii, ARL, 2800 Powder Mill Road, Adelphi, MD 20783

Reported scientific results indicate that laser ceramic technology has matured to the level when laser gain elements can be viewed as “fully engineerable” components of laser design. Variety of activating ions in ceramics to include Nd^{3+} and Yb^{3+} ions for gain and Cr^{4+} ion for Q-switching saturation were tested in numerous laser setups. Ceramics can also be manufactured with high Nd^{3+} concentrations (not available in single-crystalline form), which has high potential for “thin-disk”-like laser architectures.

This presentation gives an overview of experimental laser results obtained at ARL with particular emphasis on highly-concentrated Nd:YAG ceramics and laser designs accommodating this approach.

5.7.4 Polycrystalline YAG: Laser Host Material

HeeDong Lee, Tai-Il Mah, and Triplicane A. Parthasarathy, UES, Inc. Dayton-Xenia Road, Dayton, Ohio 45432

New HPSSL host materials are urgently needed for various applications. Dense, polycrystalline YAG doped with various rare earth elements is a strong candidate, and a process that enables the production of dense, polycrystalline YAG is now feasible. However, there still remain various technical barriers to attaining optical transparency that is comparable to single crystal YAG. Two strict requirements, a process of fabricating highly sinterable, high purity YAG powder and a robust densification process, need to be met. To resolve these two most important issues, we have developed a novel combustion process for YAG powder synthesis as well as a two-step densification process. By combining these two technologies, transparent polycrystalline YAG doped with 1~ 2 at.% Nd was successfully fabricated, resulting in a high optical transparency comparable to that of the single crystal. The green body was first sintered at 1550 to ~1650 °C for a few hours, and further HIP in the same temperature range to obtain full density. The results of microstructural characterization (scanning electron microscope (SEM)), phase identification (X-ray diffraction (XRD)), and visible and infrared transmittance will be presented, along with a discussion of the processing variables.

5.7.5 High Purity, Unagglomerated Nanopowders for Implementation in High Energy Laser Systems

Todd Polley, Vice President of Electronics & Optics, *n*Gimat Company, 5315 Peachtree Industrial Blvd., Atlanta, GA 30341

*n*Gimat has demonstrated a scaleable, cost-effective manufacturing process for producing high purity YAG and Nd-doped YAG nanopowders. Through collaborations with Penn State and

VLOC, these powders are being utilized to fabricate fully dense, high transmission ceramics for laser applications. *n*Gimat has rapidly achieved high quality YAG nanopowders due to the unique flexibility of the proprietary NanoSpray^{SM} process and *n*Gimat's ability to tailor materials composition and architecture on the nanoscale. *n*Gimat has utilized this capability to develop and deliver a wide variety of nanoengineered powders in volume (>10 kg) and at low relative cost.

5.7.6 Agiltron Laser Ceramics Development

King Wang, Agiltron, Inc., 15 Cabot Rd, Woburn, MA 01801

Agiltron is an industry-leading producer of advanced electro-optic ceramics and devices. Recently, this company has successfully fabricated Nd:YAG ceramics and preliminarily evaluated their micro-structures and optical performance. Agiltron transparent Nd:YAG ceramics were vacuum sintered from commercially available highly sinterable, non-agglomerated, nanopowder, prepared using flame spray pyrolysis (FSP). The ceramics show high transparency of 75% and long fluorescence lifetime of ~230 μs, which are close to those of commercial Nd:YAG ceramics of the same Nd doping concentrations. Several light scattering mechanisms have also been identified.

5.7.7 Issues and Opportunities for Using Custom Formulated Nanopowders to Prepare Nanostructured Transparent Ceramics

Anthony C. Sutorik, Nanocerox, 712 State Circle, Ann Arbor, MI 48108

Strategies to influence bulk properties through control of structure and composition at the nanoscale (<100 nm) can offer several advantages to the reliable preparation of transparent ceramics for many applications, including laser technology. Nanoscale compositional and structural uniformity would reduce the formation of second phase impurities, which would otherwise degrade the optical properties of the bulk ceramic. Appropriate processing of nano-sized starting powders can limit the size of light scattering centers to less than the wavelength of visible light, thereby contributing to higher ceramic transparency. Also, decreased scattering from nanoscale features may enable transparency for ceramics with non-cubic crystal structures, thereby expanding material choices for advanced devices. Nanocerox specializes in the research and commercial development of custom formulated mixed-metal oxide nanopowders for a variety of applications. Using liquid phase precursor solutions for synthesis with FSP, our production method can produce oxide nanopowders (average particle size (APS) ≤ 50 nm) of several candidates for ceramic transparency including Y_2O_3, $MgAl_2O_4$, and $Y_3Al_5O_{12}$. This presentation will highlight nanopowder characteristics of purity, composition, phase behavior, and particle morphology; and will also describe some of our early attempts to identify and address processing and sintering issues.

6. Selected Papers

6.1 Fabrication of Transparent Polycrystalline Silicon Nitride Ceramics

6.1.1 Authors

Rak Joo Sung[*], Takafumi Kusunose[†], Tohru Sekino[†], Sang Woo Kim[*], Koichi Niihara[‡], and Soo Wohn Lee[§]

6.1.2 Abstract

In the present study, we focused on fabrication of optically multifunctional silicon nitride. Silicon nitride is widely used in high temperature applications because of excellent thermo-mechanical properties. If silicon nitride has optical properties such as transparency, it can be used for optical applications at high temperature. It needs for high transparent polycrystalline silicon nitride without secondary phase and defect, whereas the silicon nitride microstructure contained elongated β-phase. β-phase grain growth and elongation must be inhibited by microstructure design for optical properties. A novel transparent polycrystalline silicon nitride was fabricated by hot-press sintering method with MgO and AlN as additives. The mixed powders with 3 wt.% MgO and 9 wt.% AlN were sintered at 1900 °C for 1 h under 30 MPa pressure in a nitrogen gas atmosphere. The resulting polycrystalline silicon nitride showed superior properties, such as about 65% transmittance at wavelength of 2.5 μm in 300 μm thickness.

6.1.3 Keywords

Silicon nitride, MgO, AlN, hot-press, transparency

6.1.4 Introduction

Silicon nitride ceramic is a main ceramic among nitride ceramics due to its good thermal shock resistance and high corrosion resistance. It also has excellent abrasion resistance, low thermal expansion, medium thermal conductivity, and very good chemical resistance. These properties could be used for extreme application conditions. Silicon nitride is sintered by liquid phase sintering because the solid-state diffusion is very slow (Kijima and S. Shirasaki, 1976). This use of sintering additives changes the properties of hot-pressed silicon nitride ceramic markedly. A kind and amount of composition of the additives are not only of decisive influence on the

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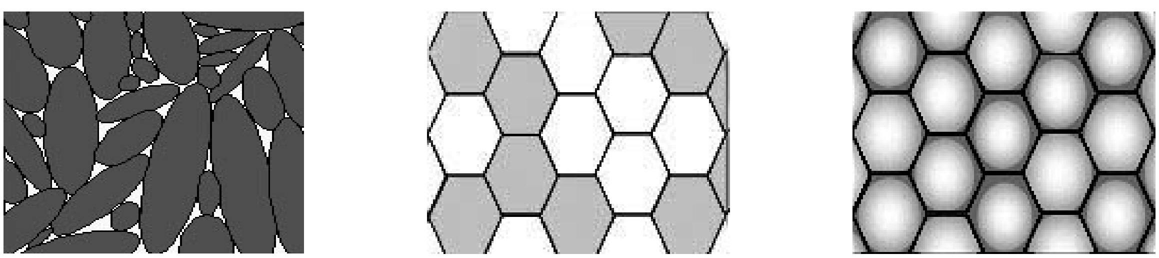
[*] Nano-Materials Research Center, Korea Institute of Science and Technology, Seoul 136-791, Korea.
[†] The Institute of Scientific and Industrial Research, Osaka University, Ibaraki, Osaka 562-0047, Japan.
[‡] Extreme Energy-Density Research Institute, Nagaoka University of Technology, Niigata 940-2188, Japan.
[§] Department of Materials Engineering, Sun Moon University, Asan, ChungNam 336-708, Korea.

sintering parameters (temperature, pressure, time, atmosphere), but also on the resulting phase relations and microstructures.

Properties of sintered silicon nitride ceramics are affected by microstructures such as grain, grain boundary, pore, and secondary phase. Mechanically and thermally functional silicon nitride can be fabricated by abnormal grain growth, high aspect ratio as shown in figure 45a. For the formation of elongated β-Si_3N_4 grains, nucleation and growth can be controlled by sintering process during the α- to β-phase transformation (Mitomo and Mizuno, 1986; Tani et al, 1986; Li and Yamanishi, 1989; Kawashim et al., 1999). Magnetically functional silicon nitride can be fabricated with secondary phase dispersion and grain distribution as shown in figure 45b. Electrically multifunctional silicon nitride can be developed with grain boundary modification and homogeneity (Kawaoka et al., 2001; Kawaoka et al., 2004; Kim et al., 2005), as shown in figure 45c.

Coble (1962) first made translucent Al_2O_3. Since then, a number of oxide and nitride ceramics have been developed for optical and other applications (Bratton, 1974; McCauley and Corbin, 1979; Kuramoto et al., 1989; Granon et al., 1995; Shimada et al., 1996; Li et al., 2000; Apetz and van Bruggen, 2003). Silicon nitride ceramic is usually opaque. To obtain transparent ceramic, efforts should be made to eliminate or minimize scattering and absorption of light. The microstructure of dense silicon nitride ceramic depends strongly on both of the starting powder, and sintering technique. To fabricate optically multifunctional silicon nitride, microstructure design needs with high dense sintered body and homogeneous grain distribution to decrease scattering by pores, secondary phases, and optical anisotropy.



(a) (b) (c)

Figure 45. Microstructure design on multifunctional silicon nitride ceramic: (a) mechanical and thermal, (b) magnetical, and (c) electrical multifunctional properties.

6.1.5 Experimental Procedures

High purity α-Si_3N_4 powder (SN-E10, Ube Co., Japan) was used as a starting material. It was mixed with various amounts of MgO (Ube Co., Japan) and various amount of AlN (Grade F, Tokuyama Co., Japan). The properties of starting powders are listed in table 4.

Table 4. Properties of starting powders.

	Si_3N_4	MgO	AlN
Average diameter (μm)	0.2	0.05	
Specific surface area (m^2/g)	11.2		3.37
Purity (%)	> 99.5	> 99.9	> 99.99
Impurity (ppm)	Cl < 100	C < 5	C 320
	Fe < 100	Fe < 5	Fe < 10
	Ca < 50	Zn < 5	Ca 8
	Al < 50		Si 9
α-phase content (%)	> 95		

These powders were mixed in a polyethylene bottle with high purity Si_3N_4 balls and ethanol for 24 h. The slurry was dried in a rotary evaporator and dry ball-milled with high purity Si_3N_4 balls for 12 h. These powders were packed into the carbon mold and hot pressed under a pressure of 30 MPa, using a graphite die at 1900 °C for 1 h in an N_2 atmosphere.

The density of hot pressed silicon nitride was measured by the Archimedes Method using toluene at room temperature. The relative density was calculated on the basic of the theoretical density derived from each individual constituent and its content.

Reaction of MgO and AlN was verified by high temperature XRD analysis using an Advanced Diffraction System (SCINTAG, Inc., USA). Crystalline phases and volume fractions of α- or β-Si_3N_4 were determined by XRD analysis using a RIGAKU Rotaflex Diffractormeter (RU-200B, RIGAKU Co., Ltd., Japan) with a CuKα (λ=0.15418 nm) operated at 50 kV and 150 mA. The 2θ angle-scanning rate was 4 °C/min, and the identification of phases present in specimens was referred to Joint Committee on Powder Diffraction Standards (JCPDS) data.

The volume fraction of α- or β-Si_3N_4 was calculated on the basic of the two highest XRD peaks of α-Si_3N_4 and β-Si_3N_4 as following:

$$V_{\alpha} = \frac{I_{\alpha}(210)}{I_{\alpha}(210) + I_{\beta}(210)} \tag{1}$$

The transmittance was measure by ultraviolet (UV) spectra photometer in the measuring range from 200 to 2500 nm.

Sintered specimens were polished to 0.5 μm, chemically etched in NaOH, molten at 350 °C for 3 min and then coated gold (Au). Microstructure and fracture surface were observed by SEM (S-5000, Hitachi Co., Ltd., Japan).

6.1.6 Results and Discussion

The relative density of hot pressed silicon nitride was over 99%, and it could be sintered with the high density. α-Si_3N_4 and β-Si_3N_4 were determined by XRD analysis of the hot pressed silicon nitride as shown in figure 46. In the case of 0 wt.% content of AlN, only β-Si_3N_4 was found. It means that β-Si_3N_4 perfectly transformed into α-Si_3N_4. All α-phase was transformed into β-phase at 1900 °C with 0 and 1 wt.% amount of AlN. α-Si_3N_4 peaks appeared from 3 wt.% of AlN. The volume fraction of β-Si_3N_4 decreased with increasing the amount of AlN. At 9 wt.% AlN, the volume fraction of α-Si_3N_4 is much more than that of β-Si_3N_4. The volume fraction of α-Si_3N_4 was determined by the method of Gazzara and Messier and shown in table 5 (Gazzara and Messier, 1977). The results indicated that the α-phase content increased invariably with increasing the amount of AlN. Also it was very difficult to search the peaks of MgO and AlN after hot pressing, because they were dissolved in the grain and grain boundary. The crystal lattice of β-Si_3N_4 can accommodate other atoms, both metallic and nonmetallic, in large amounts.

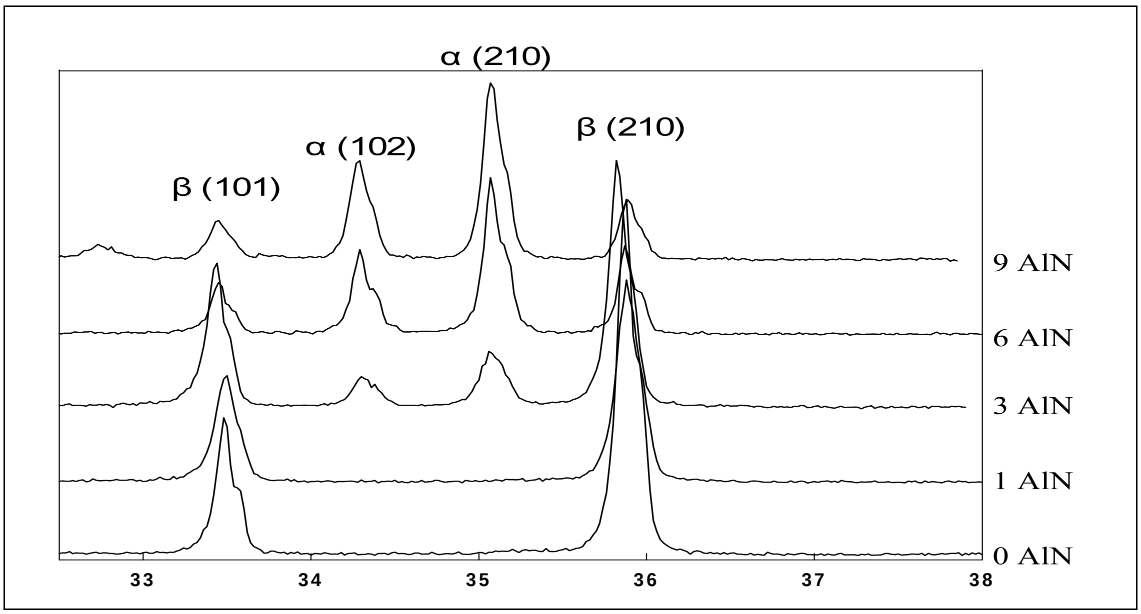


Figure 46. XRD patterns of the hot pressed silicon nitride with various contents of AlN.

Table 5. Volume fraction of α-/β-phase of hot pressed silicon nitride with various AlN additives.

	α-phase (Vol.%)	**β-phase (Vol.%)**
0 AlN	0	100
1 AlN	0	100
3 AlN	18	82
6 AlN	63	37
9 AlN	75	25

Since silicon nitride is difficult to be fully densified due to their strong covalent bonding, it is commonly densified through liquid phase sintering by adding sintering additives. MgO and AlN were selected as sintering additives for fabricating transparent polycrystalline silicon nitride ceramics. MgO addition has a significant effect on the densification of Si_3N_4 in the pressure sintering. We added MgO and AlN into starting powder. It reacted from 1200 °C as shown in figure 47.

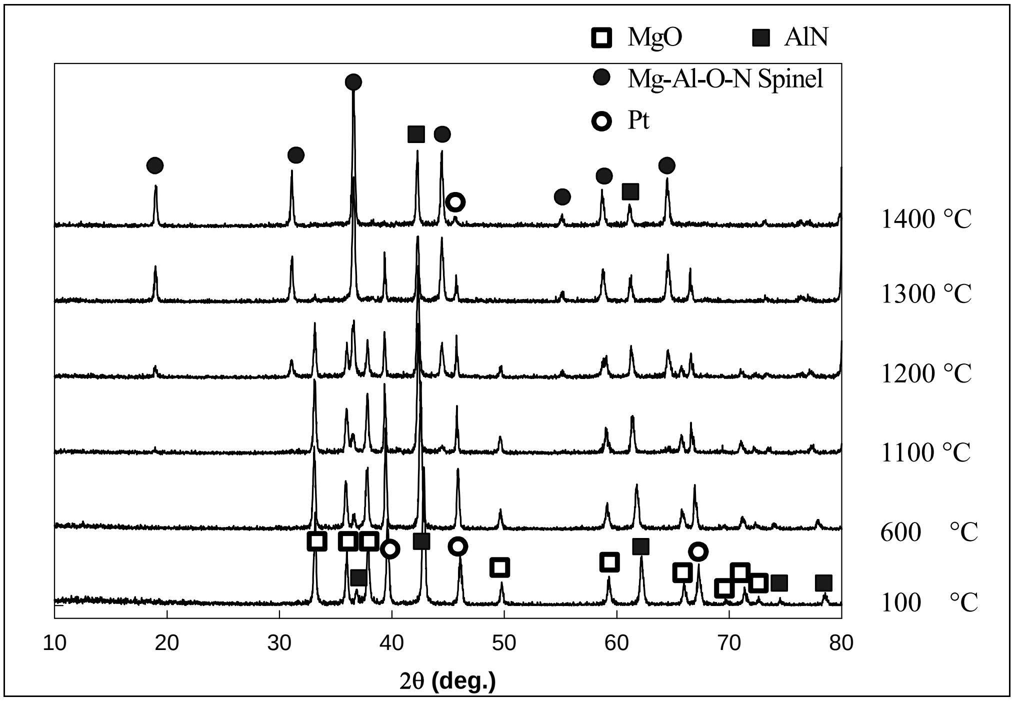
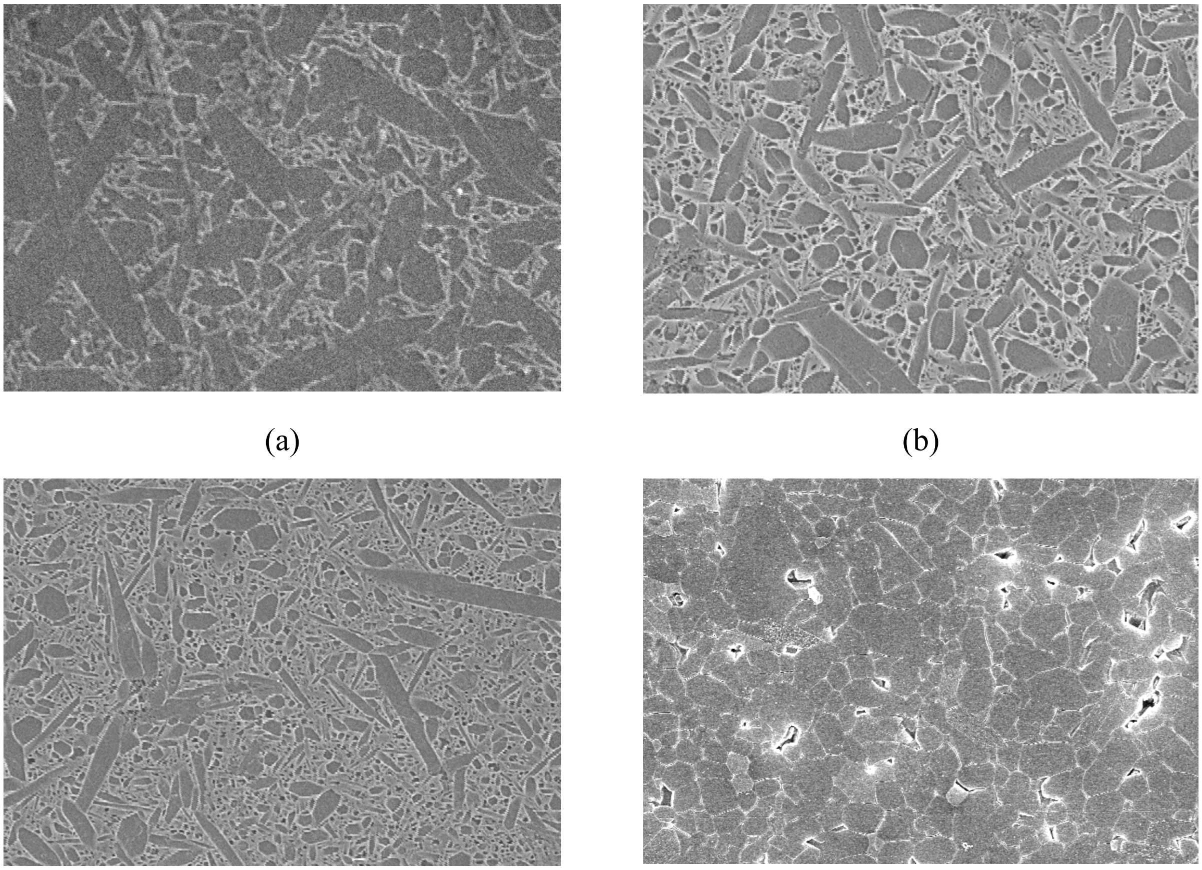


Figure 47. XRD patterns of MgO-AlN mixed powders at various high temperatures.

In the sintering of Si_3N_4 ceramics, the solution-diffusion-reprecipitation process is occurred through the liquid phase. The solution-diffusion-reprecipitation is a main mechanism for the Si_3N_4 phase transformation, especially for the growth of β-Si_3N_4. Sintering additives become liquid phase with increasing the temperature and liquid phases cover α particles as a starting powder. Usually, α particles dissolved in the liquid phase and then precipitated as particles during the cooling step. Reacted Mg-Al-O-N had influence on dissolved α particles. α-Si_3N_4 couldn't dissolve plentifully. Finally, amount of precipitated β-Si_3N_4 decreased.

Figure 48 shows SEM micrographs of the etched surface of silicon nitride depending on the amount of AlN. The large elongated grain of β-Si_3N_4 decreased with increasing the amount of AlN. In the case of 9 wt.% content of AlN, it has many pores comparing with other contents. The microstructure has a significant influence on the characteristic properties of a material. Type, amount, arrangement, size, shape, and orientation of the various phases all contribute to the actual microstructure.



(a) (b) (c) (d)

Figure 48. SEM micrographs of the etched surface for silicon nitride with various content of AlN: (a) 0 wt.%, (b) 1 wt.%, (c) 3 wt.%, and (d) 9 wt.%.

We found that transparent polycrystalline silicon nitride can be sintered with 3 wt.% MgO and 9 wt.% AlN. Microstructure of transparent polycrystalline silicon nitride depends strongly on the grain shape and size distribution. It has a highly dense structure, with small, uniform 75% α- and 25% β-phase grains as well as pores. Figure 49 shows optical images and transmittance of transparent silicon nitride depending on thickness. The maximum transmittance, 65%, is observed at 2.5 μm in the infrared region. The transmittance decreased with increasing the thickness of specimen. We observed the pores on the etched surface of transparent polycrystalline silicon nitride.

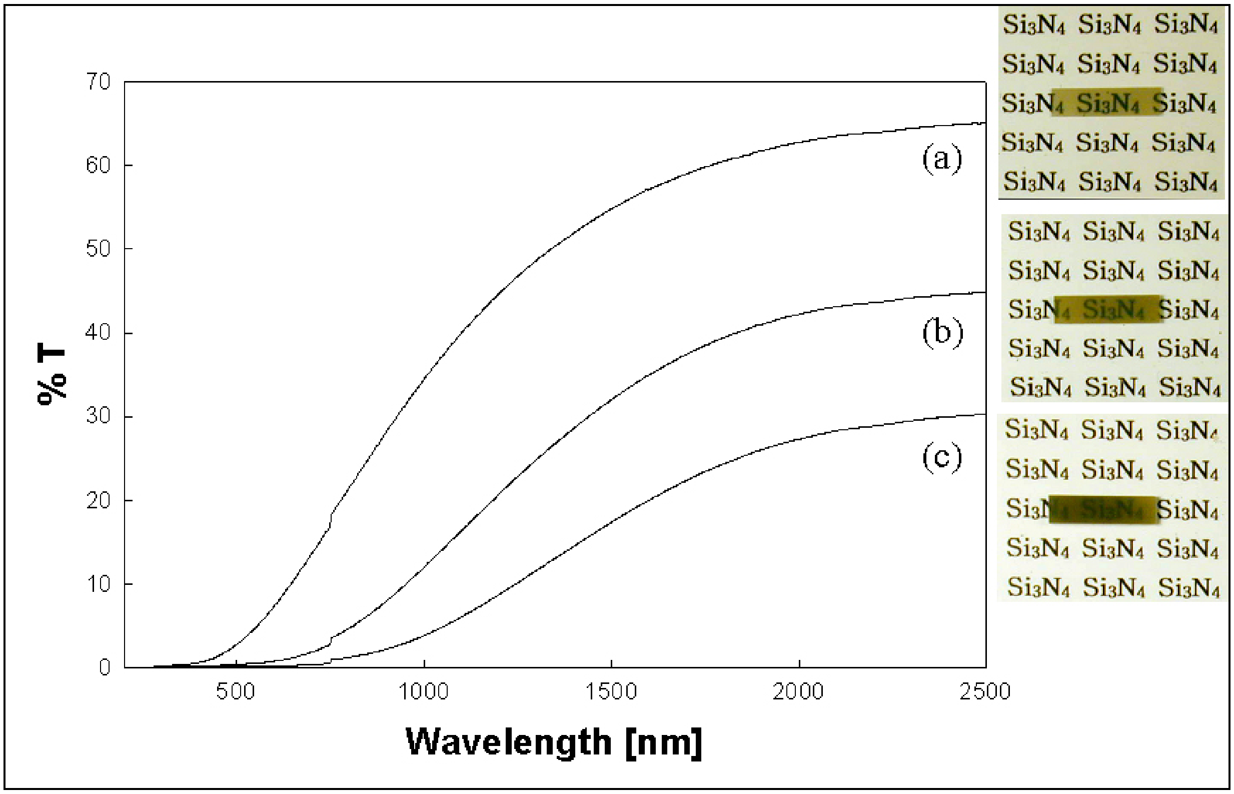


Figure 49. Optical images and transmittance of transparent silicon nitride depending on thickness: (a) 300 µm, (b) 600 µm, and (c) 1 mm.

6.1.7 Conclusions

Transparent polycrystalline silicon nitride was successfully fabricated by microstructure design. It was sintered by hot press sintering method at 1900 °C with adding 3 wt.% MgO and 9 wt.% AlN as sintering additives. The maximum transmittance, 65%, was obtained at 2.5 µm in the infrared region. The transmittance decreased with increasing thickness of specimen. Transparent polycrystalline silicon nitride consists of 75 vol.% α-phase Si_3N_4 and 25 vol.% β-phase Si_3N_4. α-phase Si_3N_4 couldn't transform into β-phase Si_3N_4 because of the react of MgO-AlN at 1200 °C.

6.2 Failure Waves and Their Possible Roles in Determining Penetration Resistance of Glass

6.2.1 Author

Stephan J. Bless, Institute for Advanced Technology, The University of Texas at Austin, Austin, TX 78759

6.2.2 Abstract

High-velocity impact can produce FWs in glass. FWs limit the speed at which a glass target can become comminuted. The resulting time-dependence of strength is likely to influence resistance to ballistic penetration.

6.2.3 Introduction

In recent years, there has there has been a large demand for improved transparent armor. The conceptual framework for transparent armor design still comes largely from investigations of indentation and low-speed impacts on glass. The dominant failure sequence under those conditions is formation of a cone crack that initiates around the periphery of the indenter. Additional loading produces either additional cone cracks or median cracks, depending on the amount of ductility. Cone cracks (figure 50) form around the periphery of spherical indenters.

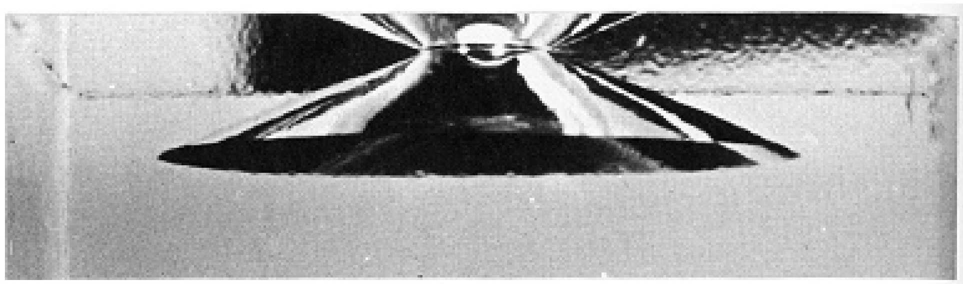


Figure 50. Cone cracks in glass (Roesler, 1956).

6.2.4 Failure Fronts Produced by Projectile Impact

Under high-speed impacts, fracture and damage propagation occur over time scales commensurate with the applied loads, leading to new phenomena. For example, photographs of impacts at higher speeds into transparent brittle materials often show a dark zone that propagates away from the impact site. This zone often stops and evolves into a dense crack array, as shown in figure 51. These advancing failure zones are referred to as a failure wave. The first mention of the concept of a “failure wave” apparently occurs in Russian publications dating from the 1960s, such as Galin et al. (1966), Nikolaevskii (1981), and Cherepanov (1979), where “self-propagating failure fronts” are discussed.

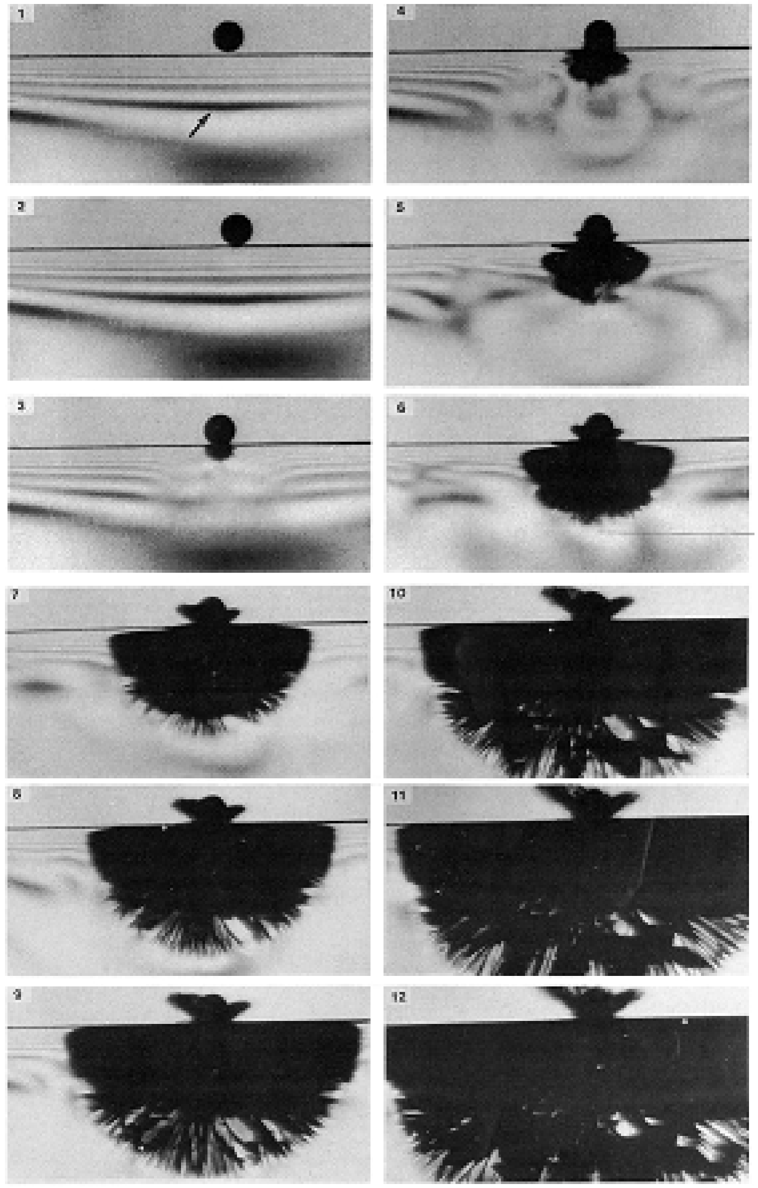


Figure 51. Impact of sphere on a half-space; comminuted region propagates into glass at high speed (Chandrasekar and Chaudri, 1994).

Many other observations of impact-induced damage can also probably be interpreted as FWs. In figure 52, a two-layer glass target is penetrated by a shaped charge jet, and the jet has penetrated into the second layer. A failure front is penetrating inward (to the left) from the impact surface, and also backward from the glass/glass interface. The speed of this failure front in about 2 km/s. Figure 53 is a side view of a glass block struck by a high-velocity rod. There are two failure regions propagating into the block, one from the front and one from the rear. Figure 54 shows images from penetration by a tungsten rod at about 1.4 km/s. An FW that begins with a spherical front consumes the first of two glass plates. When the projectile arrives at the interface (Frame 33), a plane FW erupts from the interface and advances into the second plate.

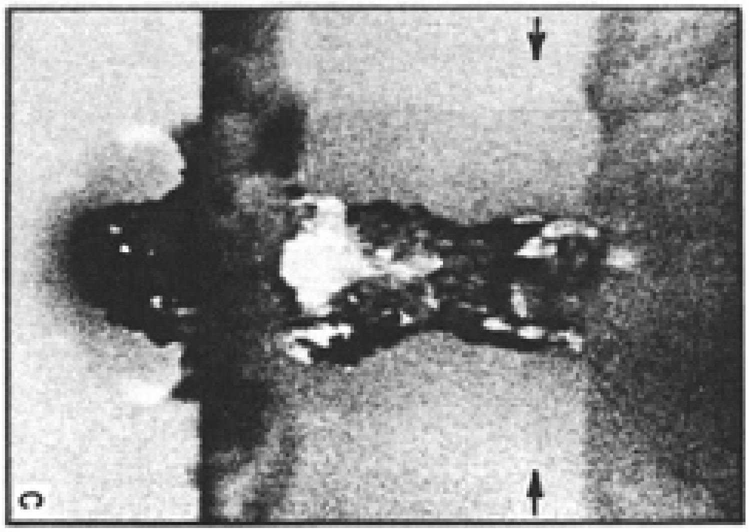


Figure 52. Hypervelocity penetration (Hauver et al., 1991); shaped charge jet enters glass from the right.

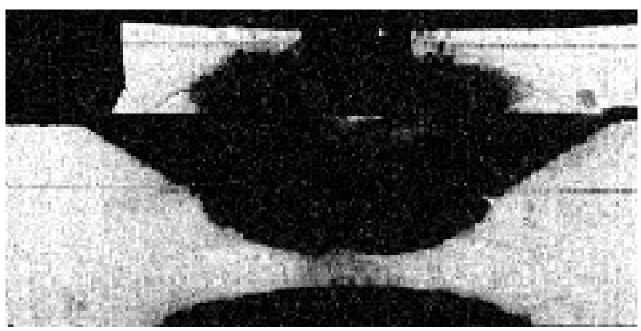


Figure 53. Impact of a blunt steel projectile on glass at 700 m/s; projectile strikes top surface and the FWs propagate from impact side and back side (Vlasov et al., 2002).

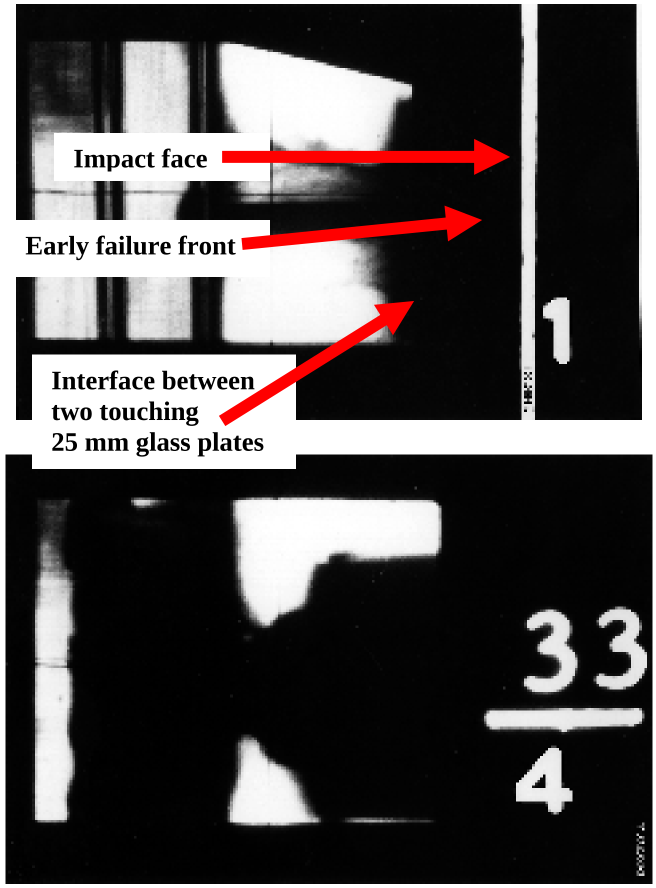


Figure 54. Impact of a tungsten rod onto two glass plates at about 1.4 km/s; projectile moves right to left.

The above examples were for impacts onto half spaces, but FWs can also apparently be produced in plane stress. Figure 55 shows two images from impacts onto the edge of glass plates—from a conical and a blunt nose projectile. The conical nose projectile produces a front of propagating needle cracks, such as has been recovered from impacts onto glass armor (Bless et al., 2007a), while the blunt projectile produces a large failed region whose advance apparently involves nucleation of damage ahead of the region that is already wholly damaged.

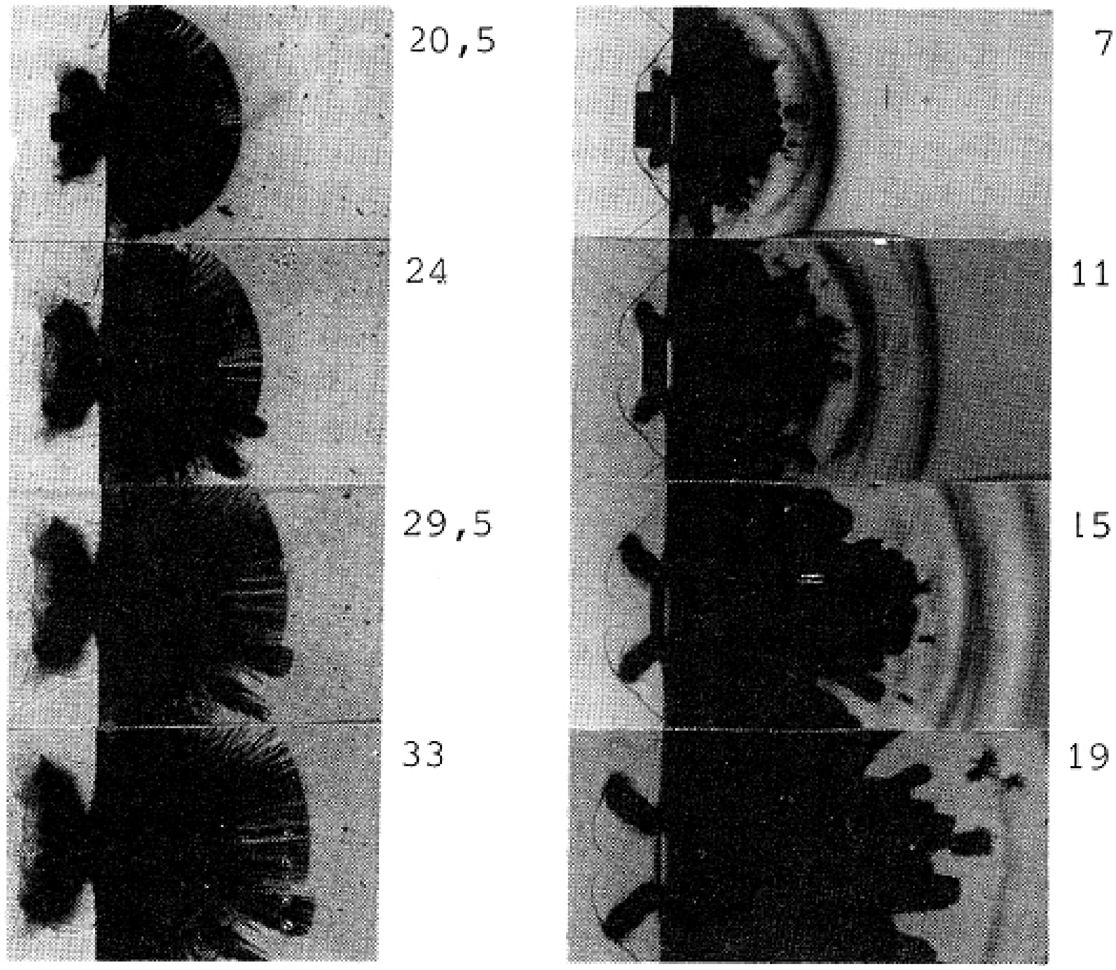


Figure 55. Two images from impacts onto the edge of glass plates—from a conical and a blunt nose projectile (Hornemann et al., 1984).

From these and other observations, the properties of the moving failed zone are usually found to include the following:

- It is apparently a region where the glass has been comminuted (broken into very small particles), and
- It moves with a characteristic velocity that often exceeds the normal maximum crack speed (about 1500 m/s for most glasses).

6.2.5 Properties of Failure Waves Determined by Plate Impact Tests

Reports of scientific investigations of FWs began appearing in the early 1990s. The first experiments were plate impact tests conducted by Gennady Kanel. (Readers unfamiliar with plate impact test techniques are referred to one of several recent review publications (Kanel et al., 2004; Meyers, 1994)).

Kanel communicated his early experiments to the author at a conference in 1990 and later published them in 1991 (Kanel et al., 1992). Figures 56a and 56b are from Kanel's original figures. Figure 56a is an (*x*,*t*) diagram for impact of a copper flyer plate onto a glass target that occupies the space $x > 0$. Elastic and deformational shocks propagate into the glass sample. Kanel was looking for a reflection back from the front of the flyer plate. Instead, he observed an unexpected arrival that apparently had reflected from an interface within the target, shown as the inner dotted line in figure 56a. Experiments with different thickness samples established that the mysterious interface was moving (figure 56b). Bless and his colleagues at the University of Dayton did similar experiments and obtained consistent results (Bless et al., 1992b).

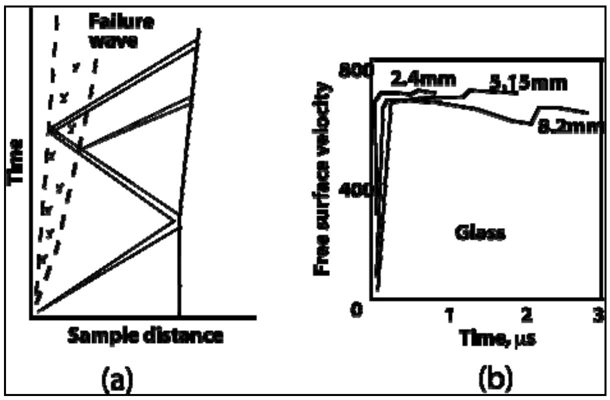


Figure 56. (a) Diagram of original FW experiment by Kanel et al., (1992) and (b) Kanel et al. (1992) results.

Subsequently, the team at Dayton conducted spall stress measurements on glass. Spall stress is also measured in the plate-impact configuration, and corresponds to the bulk tensile strength of a material (e.g., tensile failure unaffected by surface flaws). They found that the spall stress of SLS in front of the FW was extremely high—above 6 GPa. However, the spall strength behind the FWs was nearly zero. This demonstrated that the failure front separates glass that is intact from glass that has been comminuted. Soon afterward, the Dayton team also measured the shear strength in front of and behind the FW. Their results are shown in figure 57; ahead of the failure front, the shear stress was related to the principal stress by the elastic relationship, but behind the failure front the shear stress relaxed to a value a little more than 20 kbar (2 GPa). Similar measurements have now been made on many other types of glass (Bless and Brar, 2007b).

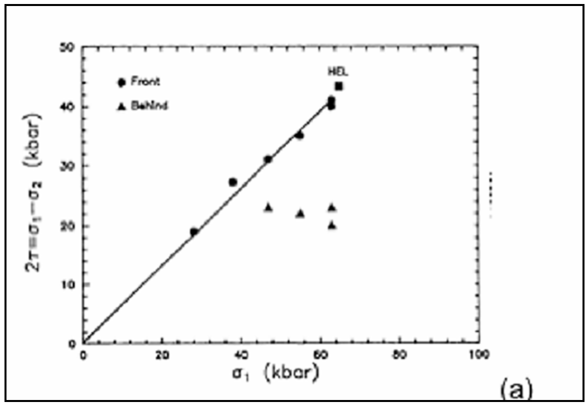


Figure 57. Stress deviator decreased—showing decrease in shear strength comminution.

Several investigators have also photographed plane FW fronts. As was the case for projectile impacts illustrated in figures 51, 55, and 56 (left), the wave fronts are smooth. They apparently advance by developing “fingers” that progress just ahead of the main front, as illustrated in figure 58 from a plate impact test. The instability of propagating fractures such as these is predicted by a recent theoretical analysis (Grinfeld et al., 2006).

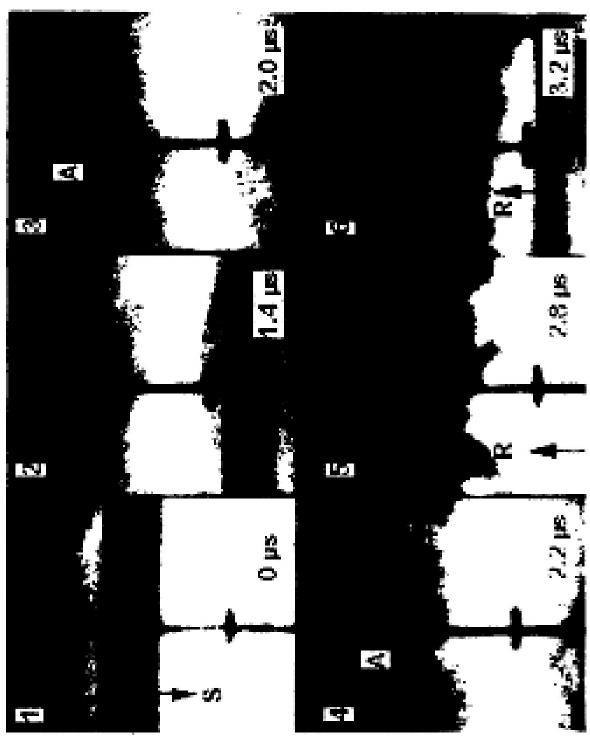


Figure 58. Photographs reveal that fronts often are not smooth (Bourne and Rosenberg, 1996); the FW moves from left to right. Time after impact is marked on the photographs; a wave shock (S) is visible in the first and second frames.

Interfaces have a significant effect on FW propagation. This was observed in projectile impact studies (see above), and also in plate impacts. It appears that FWs are generated from interfaces, as in figure 59, taken from Kanel et al. (2002). In these experiments, as the shock wave crossed each interface, FWs were generated that propagated both in the forward direction, following the shock, and in the backward direction. Failure waves are driven by stress fields—when the stress is removed by release waves arriving from free surfaces or by exhaustion of the projectile (Anderson and Orphal, 2008), they stop.

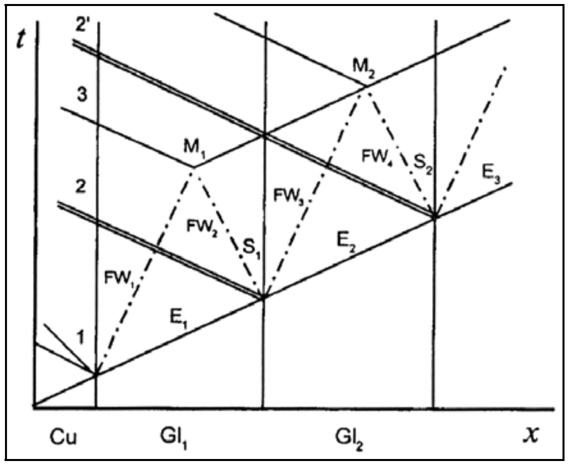


Figure 59. Diagram for copper striking glass layers, where *E* represents shocks, the double lines are release waves from closing the small gap between layers, and the FWs are generated at interfaces (Kanel et al., 2002).

Observations of FWs as revealed by plate impact tests over the past decade may be summarized thusly:

- There is a threshold stress—about half the elastic limit—for formation of FWs. (The elastic limit is not shear failure in glass; it is apparently densification.)
- Mechanical properties change little in the longitudinal direction across the FW.
- Transverse stress increases and shear stress decreases at the FW front—approaching that of a granular material.
- There is an increase in mean stress (e.g., dilatancy or bulking). (This comes about because glass normally expands when it fractures, since open cracks take up volume. In these experiments, the glass is fractured at constant volume, so it self pressurizes.)
- FWs have been observed in many different glasses, including fused silica.
- Material behind the FW has little or no tensile strength.
- FW speeds can exceed the shear wave speed. They greatly exceed crack velocities. Speed often decreases with distance.

- FW fronts are often not smooth.
- FWs can start at interfaces. They also can stop at interfaces.
- FWs are quenched by release waves.

It should also be pointed out that FWs are outside the framework of all current models for penetration of brittle materials. Until the question of the role played by FWs in ballistic transparencies is resolved, understanding derived from theoretical or numerical treatments must, therefore, be viewed cautiously.

6.2.6 Other Examples of Failure Waves

Prince Rupert's drops are one FW example that has often been used in classroom demonstrations. They are formed when liquid glass drops are quenched by dropping them into water. As a consequence, the outside is in compression, while the interior is under tension. When the tail is broken, these drops rapidly explode. The driving mechanism is apparently twofold: there is a great deal of stored elastic energy in the drop that is available to drive fragments and glass is dilatants. Figure 60 illustrates an exploding Prince Rupert's drop.

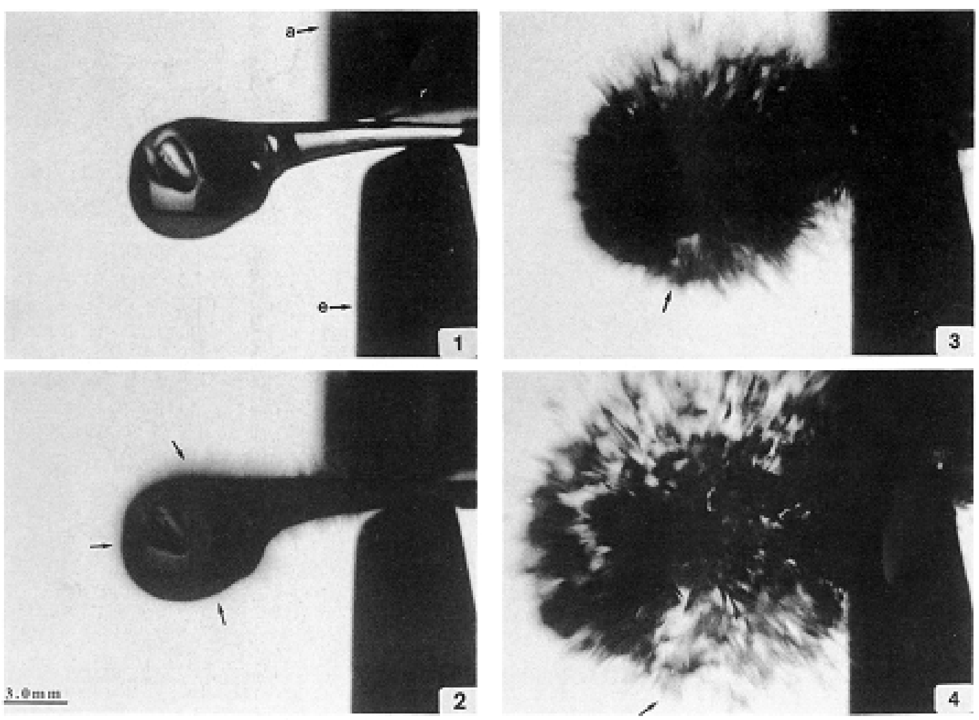


Figure 60. An exploding Prince Rupert's drop (Chandrasekar and Chaudri, 1994).

Another geometry in which FWs are observed is bars or prisms. Figure 61 shows an FW in a glass bar that has been struck on one end face by a high-speed projectile. The FW starts at the projectile interface and rapidly consumes the entire visible bar. The speed of FWs in bars seems to approach √2 times the shear wave speed.

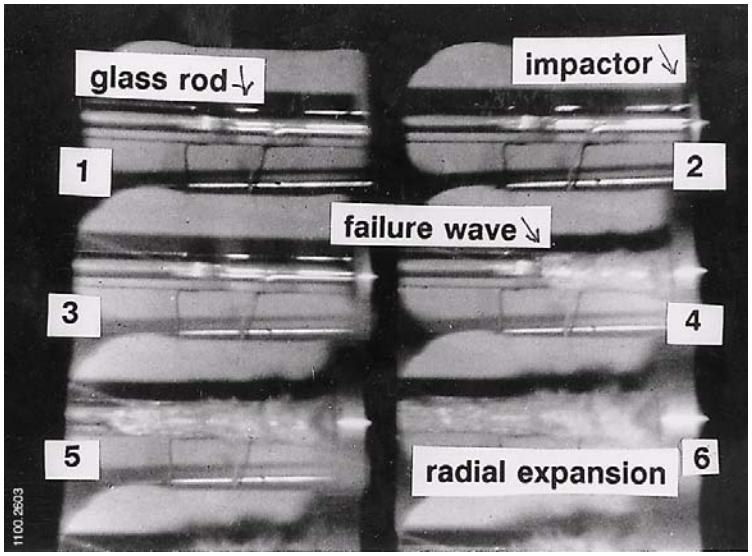


Figure 61. FW in a glass bar, with impact in Frame 2; in Frame 4, the wave is halfway across the field of view and in Frame 6, the bar has been consumed (Bless et al., 1992).

It is plausible that FWs can occur in tension, although this has not been shown conclusively. For example, figure 62 shows the FW propagating through the tensile region of a Prince Rupert's drop. Figure 63 shows a glass bar in which the distil end explodes in a tensile failure. It is interesting that the fractured material seems to differ in these two experiments. The Prince Rupert's drop produces platelets, whereas the bar produces faceted, nontransparent nuggets.

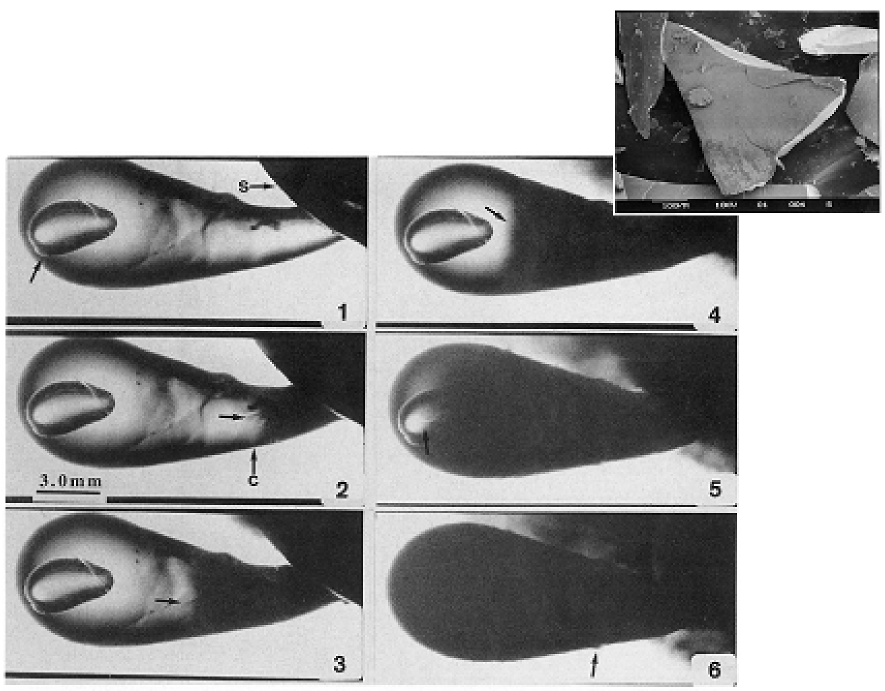


Figure 62. FW in Prince Rupert's drop and recovered particle (inset) (Chandrasekar and Chaudri, 1994).

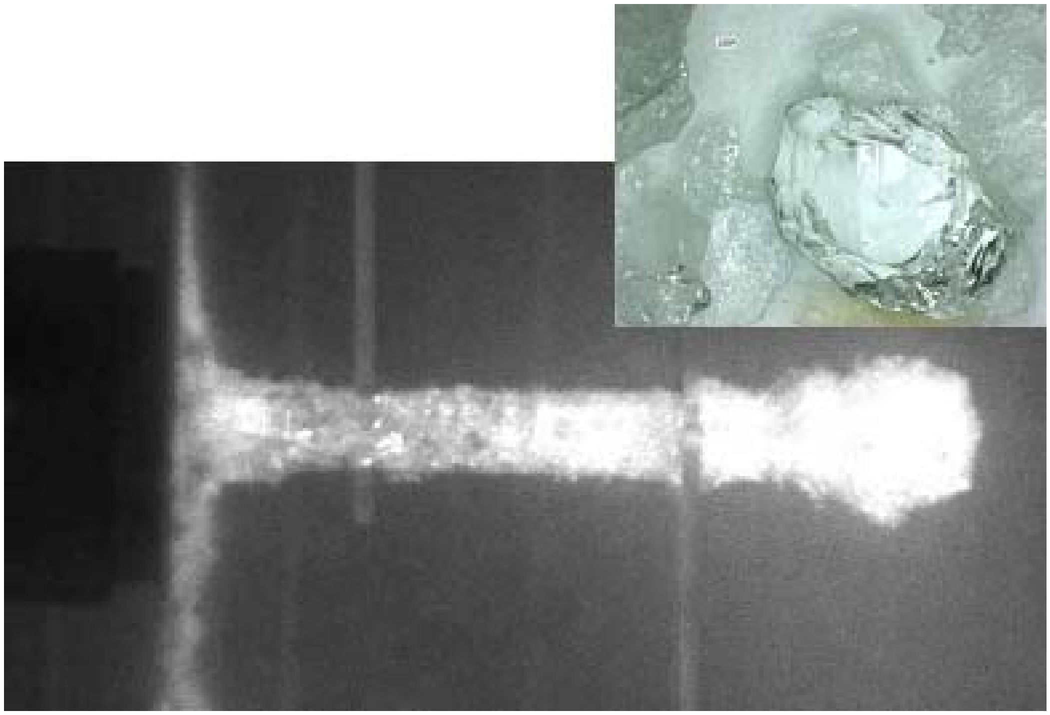


Figure 63. Float glass bar struck by projectile on left and recovered particle from distil end (inset) (Beno et al., 2005).

6.2.7 Theory

There have been several attempts to model FWs, none entirely satisfactory. Most models are phenomenological, meaning that the behavior is assumed and then described mathematically. The decrease in the stress deviator can be modeled as a drop in shear modulus (Meyers, 1994; Partom, 1998) or a decrease in strength (Espinosa et al., 1997).

Feng (2000) has modeled the FW as crack diffusion with some success. Naimark (2003) describes FWs as a possible collective behavior mode of defects under very short duration loading. Simha and Gupta (2004) consider FWs to be an example of delayed fracture that is instigated by the arrival of the primary stress wave (Grinfeld et al., 2006).

The most compelling numerical modeling of a failure wave concerned the bar impact geometry, and was accomplished by Repetto et al. (2000). In a very high-resolution calculation of individual cracks, they reproduced the failure wave evolution in glass bars. Cracks initiate according to a tensile failure criterion. The time dependence of the failure wave was controlled by a cohesive law in which strength decreased as a function of crack opening displacement.

6.2.8 Implications for Armor

Transparent armor is an example of ceramic armor. Opaque ceramic armor is normally comprised of polycrystalline ceramics, chiefly alumina, silicon carbide (SiC), or boron carbide. Conventional ceramic armor is composed of tile mosaics. The armor is normally designed so that impact damage remains confined to the impacted tile, and in this way multiple-hit performance is achieved. Transparent armor differs from these conventional ceramic armors; it is normally composed of several layers, which is the means by which multi-hit performance is achieved. Direct observation of FWs in glass laminate armor is reported in Bless et al. (2007a).

Against this background, one can speculate on the possible role of FWs for transparent armor. For thin glass layers, one would expect an enhanced vulnerability to blunt projectiles, which produce larger FWs (e.g., figure 53). In addition, there should be a critical velocity below which the armor is more effective because there is no FW. When an FW occurs, a significant volume of material is transformed into a powder around the impact site. This material offers very little penetration resistance. In a multilayer glass target, it is probable that much of the penetration resistance comes from interior layers that have not been consumed by a failure wave. When there are no interlayers to arrest the motion of FWs, most of the penetration takes place in material that has been comminuted by the FW (e.g., Anderson et al. (2005)). The decrease in penetration resistance as the target is consumed by an FW is also shown in figure 64. Most of the penetration takes place in the low-strength material.

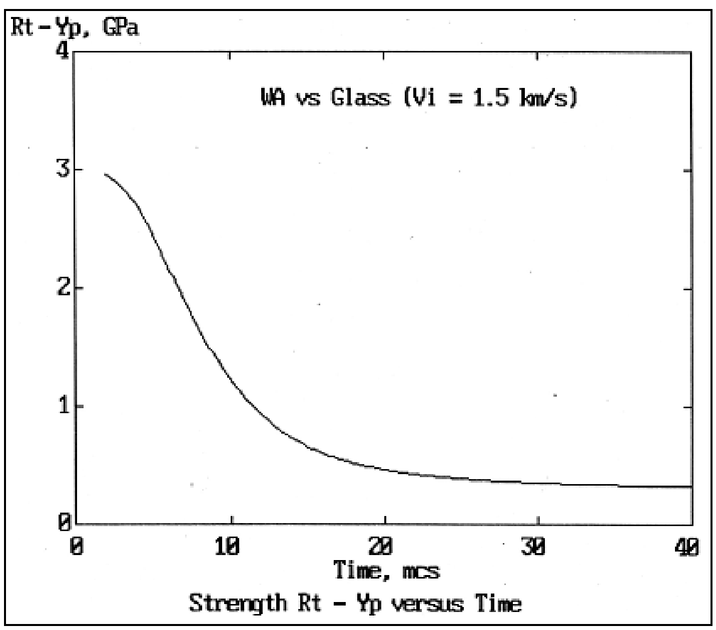


Figure 64. Effective strength of glass as a function of time after impact (Kozhushko and G. S. Pugachev, 1997).

It also follows that there is a penetration velocity above which the projectiles would move supersonic relative to the FW. Above this velocity, the glass is more difficult to penetrate. This has been demonstrated in a recent U.S.–Russian collaboration (Zilberbrand et al., 1999). Fortunately, the critical velocity is well above those normally considered as transparency threats.

The case for sharp projectiles is frankly much more speculative. The region of high compressive stress associated with a sharp impact is very limited. Failure waves from the back side of glass plates (provided they are not too thick) would be expected. Thus, glass may offer an initially very high resistance to sharp bullets, but for relatively thin tiles, the resistance of the glass may only last until the plate is consumed by the tensile failure wave. These processes may explain the fact that the tips of hard bullets are often broken by glass, but (unlike the case of ceramic armor), the body of the bullet suffers relatively little damage and is often turned sideways, as happens in sand penetration.

One hopes that better understanding of FWs will enable the design of better transparent armor. How this could come about is of course speculation at this time; however, perhaps the following concepts might be useful:

- **Suppression of FWs.** Cavity expansion models predict that superposition of compressive stress can suppress FWs (Satapathy et al., 1999). This might be achieved by surface treatments, which now can be as high as 1 GPa (Varhneya et al., 2005).
- **Ultra-pure materials.** These should have higher FW thresholds and should be examined for this effect.
- **Use of interlayers to suppress FWs.** It is clear that FWs can stop or be generated at interfaces. Suppression might greatly benefit transparent armor. The criteria have not been well investigated.
- **New materials.** Transparent polycrystals, single crystals, and glass ceramics, will soon be available. These materials should be investigated to determine if they support FWs.

6.2.9 Summary

Failure and penetration of glass by high-speed projectiles differs from static indentation in several important ways. Damage can occur not by single cracks, but by advancing networks of cracks that reduce the glass to rubble. The failure zones possess finite propagation speeds that can render the time scale for glass fracture commensurate with the impact time scale, and this may have a profound effect on the ability of the glass to stop the projectile. Understanding how failure waves are generated and propagated will probably significantly advance the scientific understanding required for efficient design of transparent armor.

6.2.10 Acknowledgement

The research reported in this document was performed in connection with Contract number DAAD17-01-D-0001 with the ARL and Award number N00014-06-1-0475 with the Office of Naval Research. The views and conclusions contained in this document are those of the authors and should not be interpreted as presenting the official policies or position, either expressed or implied, of the ARLy or the U.S. Government unless so designated by other authorized documents. Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof. The U.S. Government is authorized to reproduce and distribute reprints for government purposes notwithstanding any copyright notation hereon.

7. Briefing Charts from Plenary Session

7.1 The Impact of Research on Soldier Protection

Ms. Jill Smith, Director, WMRD, ARL, APG, MD 21005

Abstract of Briefing: The need for the Army to remain the dominant fighting force in the world is evident nowhere better than in the current environment. The demand on Army Soldiers is at an all-time high, both in time and physical strength, as Soldiers rise to meet the challenges associated with fighting the war on terrorism. To best take the fight to the enemy, the Army equips Soldiers with the most cutting-edge defensive and offensive equipment technology can provide. In the past few years, numerous developmental technologies have spiraled into the field to help Soldiers maintain the performance edge that will bring the war on terrorism to conclusion with maximum preservation of soldier lives. Ms. Jill Smith presents a number of the challenges of transforming an Army from a legacy force to a future force capable of fighting in urban terrains as well as offers technical examples of how science and engineering are transforming how Soldiers perform on the world stage. Ms. Smith's briefing is shown as figures 65–73.

Figure 65. Jill Smith of ARL provided a very important impact briefing to the visitors.

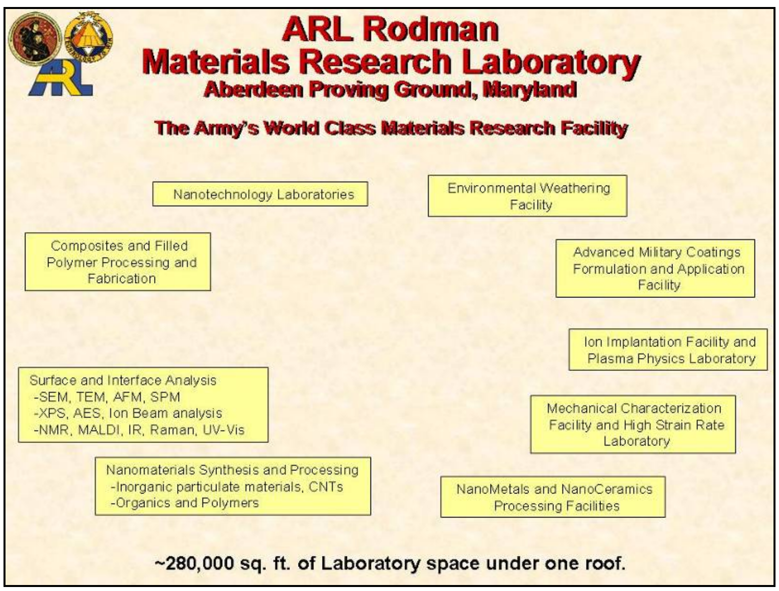


Figure 66. The technology opportunities that exist within ARL are diverse and all important to the Soldier.

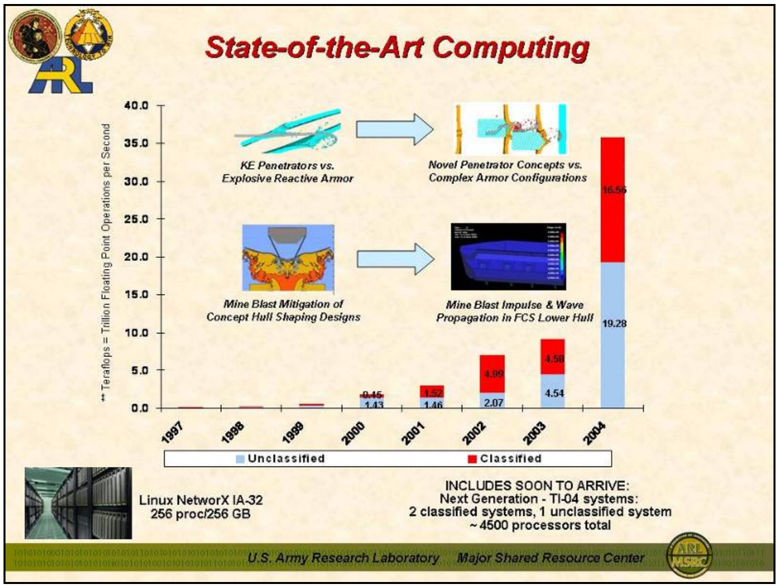


Figure 67. An emphasis continues to be made to improve computational capabilities to increase accuracy and rate of computational predictions.

Figure 68. ARL continues to impact the Soldier with fielded systems.

Figure 69. Transformation of the Army into a lighter and more agile force capable of fighting in today's urban environments requires new technological innovation.

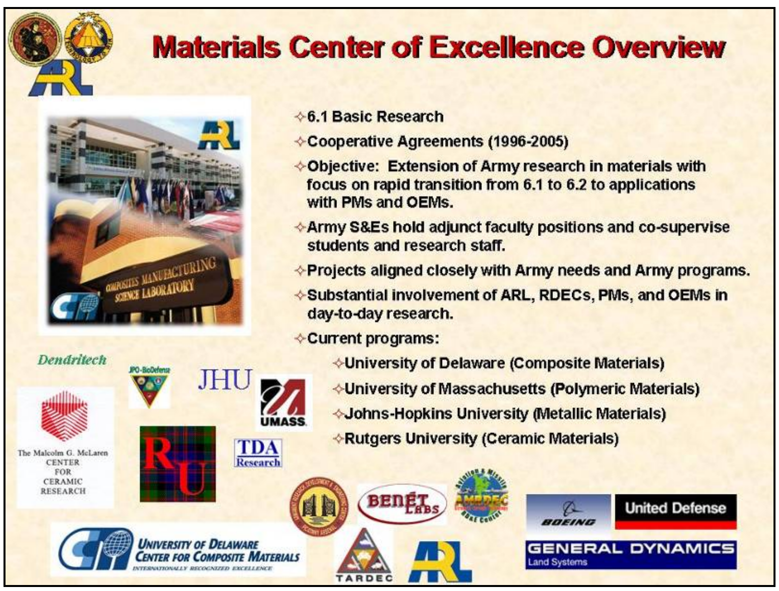


Figure 70. The Army leverages resources from academic and industrial partners to remain ahead of the transformation curver.

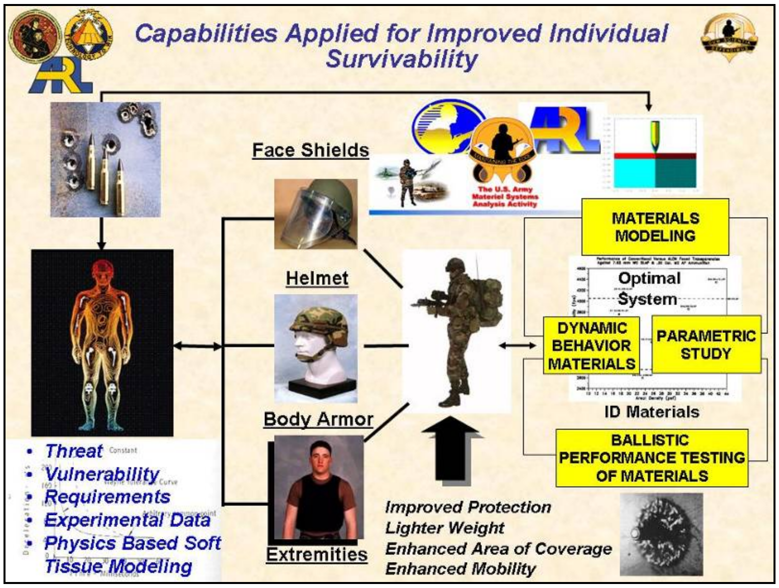


Figure 71. The Army must not only evolve the ground forces, but also the capabilities for protecting the individual Soldier.

Figure 72. Many impact technologies have been developed at ARL and pushed forward to the Soldier on point.

Figure 73. We must never forget that our responsibility is to the Soldier in the field.

7.2 The 50th Anniversary Celebration and 46th Sagamore Army Materials Research Conference

Dr. James W. McCauley, Senior Scientist, ARL, APG, MD 21005

Abstract of Briefing: Dr. McCauley introduces the theme of the 46th Army Sagamore Materials Research Conference—Advances and Needs in Multi-Spectral Transparent Materials—and highlights the importance of transparent materials technologies for the future Army. The diversity of technology needs from armor to laser host materials is emphasized. The conference takes time to evaluate the state of the art in commercial, academic and government research for materials ranging from polymers to glasses to ceramics. Dr. McCauley motivates the importance of the conference setting as a method of setting the goals for future technology developments that can have immediate and long-term impacts on soldier technology. The presentation is provided as figures 74–85.

Figure 74. The importance of Army sponsored conferences is a focus of Dr. McCauley's keynote introduction to the Sagamore meeting.

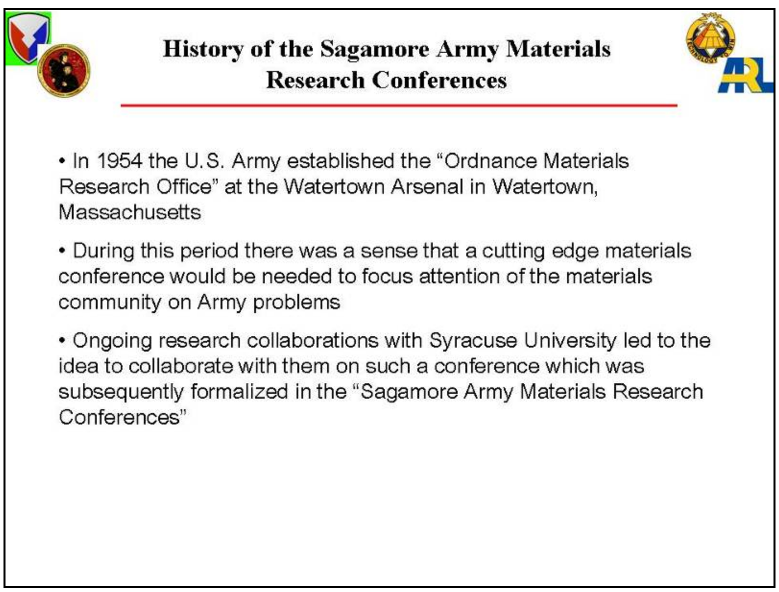


Figure 75. The history of the Sagamore meetings.

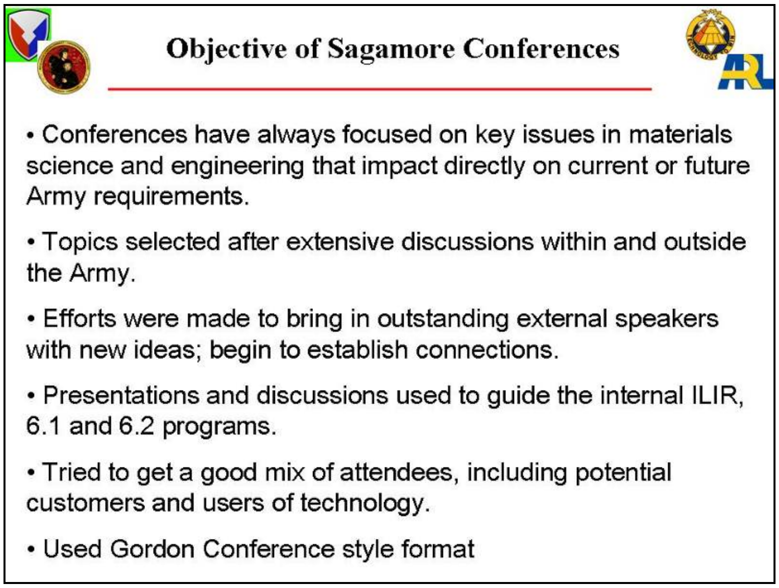


Figure 76. Sagamore Conferences have specific objectives of bringing together industry, government, and academic personnel with a specific thematic connection.

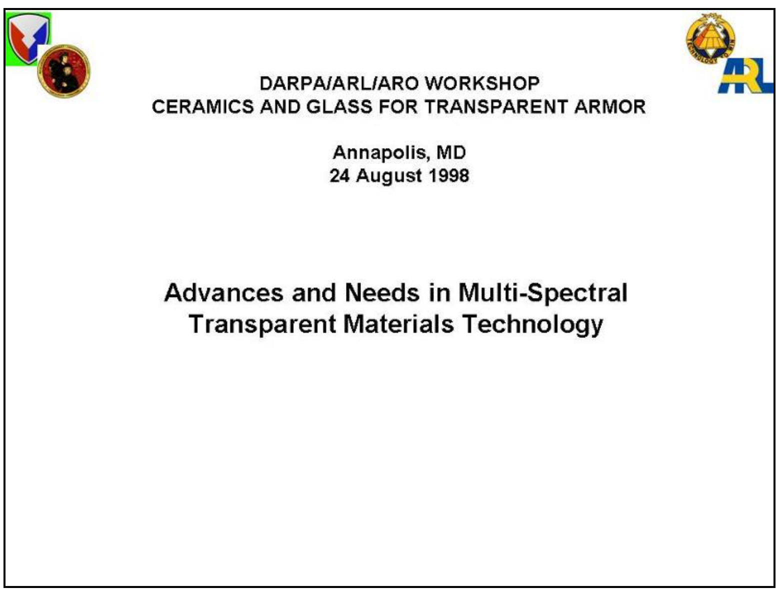


Figure 77. A previous focused meeting on transparent materials was held in 1998 as a DARPA/ARO sponsored workshop.

Figure 78. Platforms for transparent armor technologies include ground and air vehicles, and dismounted Soldiers.

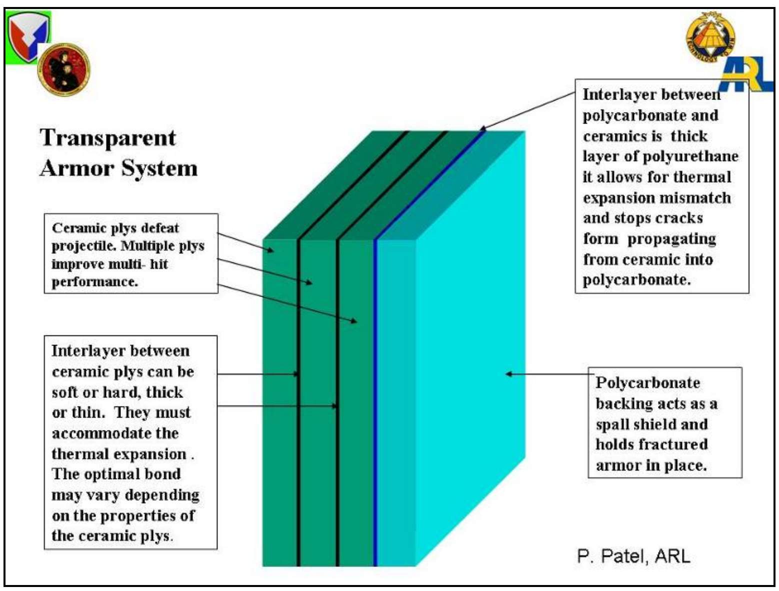


Figure 79. A generalized scheme of the transparent armor cross sections.

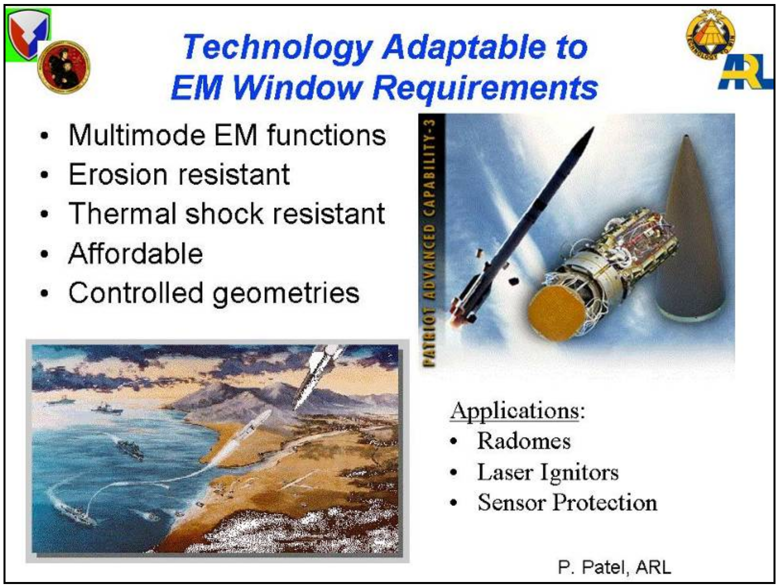


Figure 80. Electromagnetic windows include more than just armor.

Figure 81. Performance is based on field requirements for the platforms.

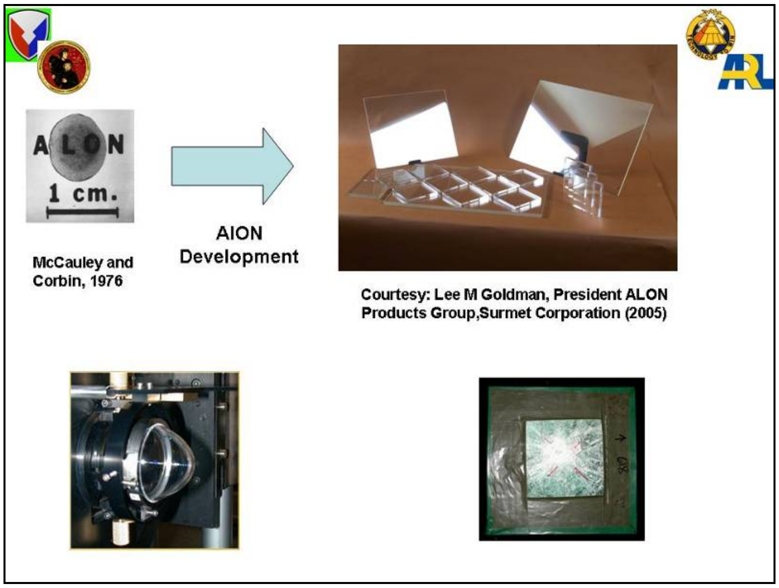


Figure 82. One of the solutions for potential for future platforms is advanced ceramics, such as AlON.

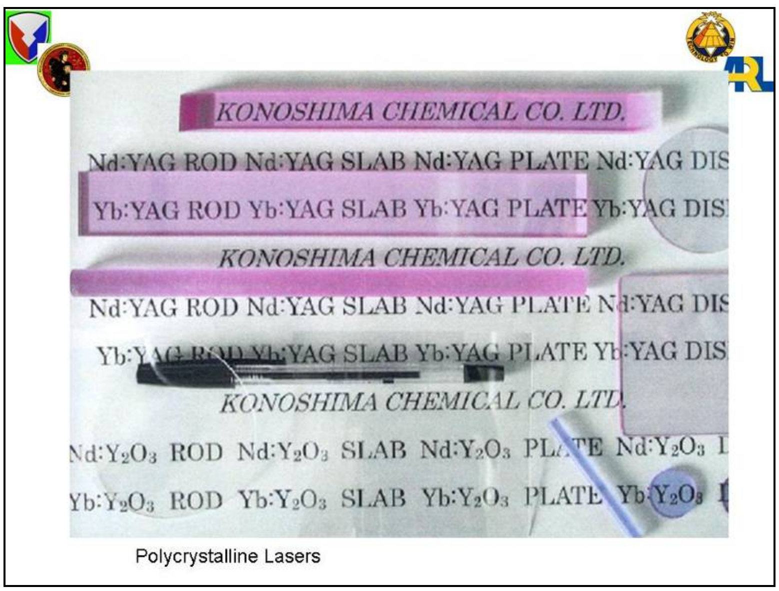


Figure 83. For laser host applications, commercial manufactures have started to sell advanced ceramics as well.

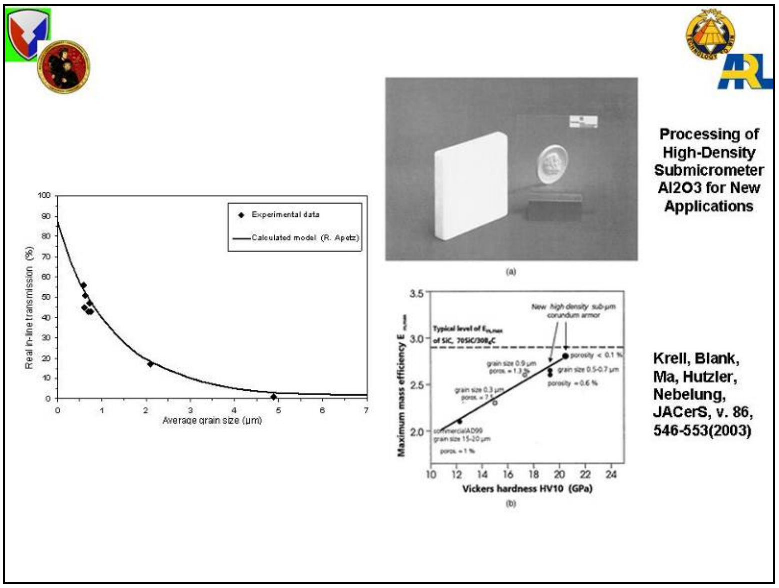


Figure 84. Methods of improving transparency in ceramics have been developed based on controlling microstructures.

50th ANNIVERSARY CELEBRATION
46th Army Sagamore Materials Research Conference
on
Advances and Needs in Multi-Spectral Transparent Materials Technology

AGENDA

Session I: Applications and Needs for Transparent Materials Technology

Session II: Transparent Electromagnetic Systems

Session III: Ceramic Processing and Industrial Panel

Session IV: Multifunctional Transparent Materials

Session V: Transparent Armor: Needs and Future Challenges

Session VI: Transparent Armor: Mechanics and Materials

Banquet Speaker: Dr. Volker Weiss

Session VII: Polycrystalline Materials for Laser Applications

Figure 85. The agenda overview for the current 50th Anniversary Celebration of the Sagamore Materials Research Conferences.

7.3 Tactical Wheeled Vehicle Add on Armor (Transparent)

Major Dan Rusin, ARL, APG, MD 21005

Abstract of Briefing: We are a nation at war. The nature of the fight has changed, and the nature of the combat response is changing, and the expectations of troops and commanders is changing to expect "armor for trucks" now and in the next war. We are an industrial nation that can provide that capability. Over the course of the calendar years 2003–2005, the U.S. Army has spent over $4 billion in Tactical Wheeled Vehicle (TWV) AoA. Over the next two years, Army TWVs will use more transparent armor than ever before. The transparencies used on the TWV AoA kits are larger than any presented areas in traditional combat vehicles. This briefing will present the setting for TWV AoA Transparent Armor requirements and begin to give an estimate of some of the needs for TWV Transparent Armor in the future. Discussion will be presented by Major Daniel Rusin, who was RDECOM's senior Uniformed Army Scientist and Engineer on the "HMMWV ASK"- (Armor Survivability Kit) project, which is now in use in combat protecting over 12,000 combat crews in HMMWVs who are restoring normalcy to Iraq. He has deployed to Southwest Asia three times and will bring experience and Soldier expectations relative to transparent armor. The presentation is presented as figures 86–113.

Figure 86. Major Rusin offered a Soldier's perspective on the importance of technology for the warfighter.

Figure 87. Protecting the lives of Soldiers is the foundation of Army research and development.

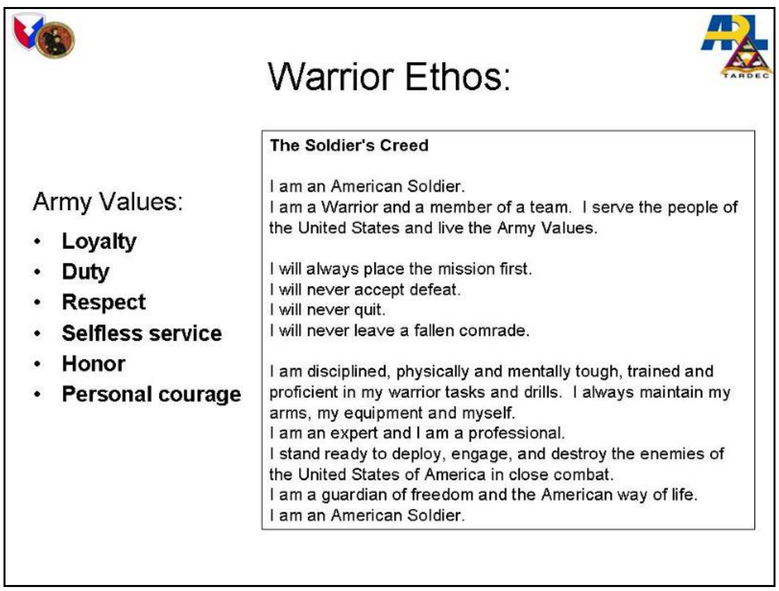


Figure 88. Soldiers live by a creed and core values.

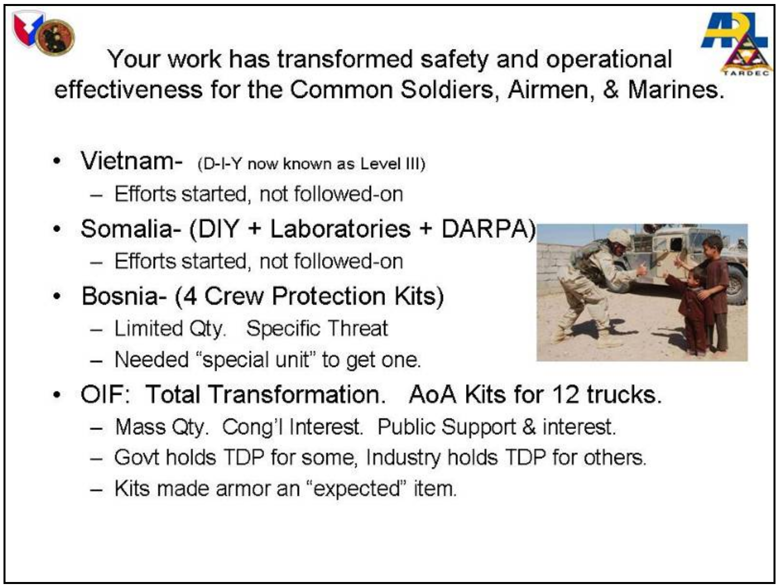


Figure 89. Research and development has made an impact in wars throughout history.

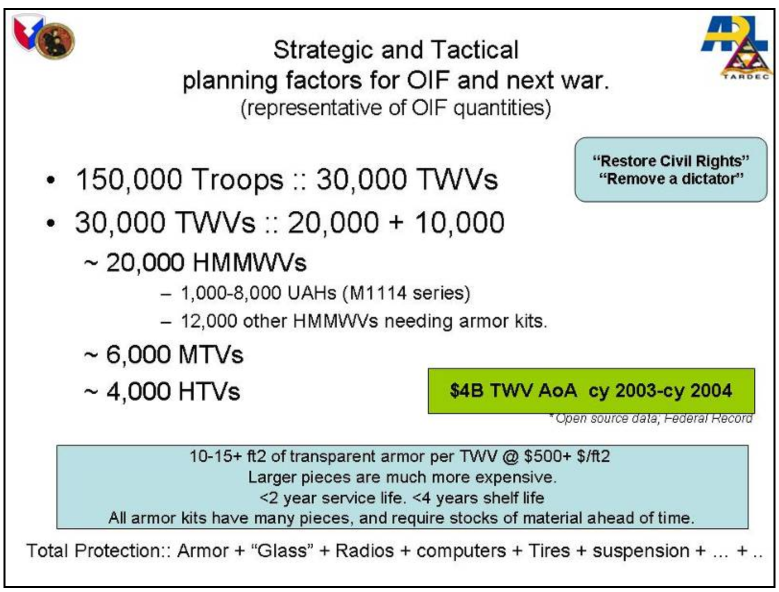


Figure 90. A recent impact story of up-armor technology for ground vehicles is presented; the impact is significant in numbers and capability.

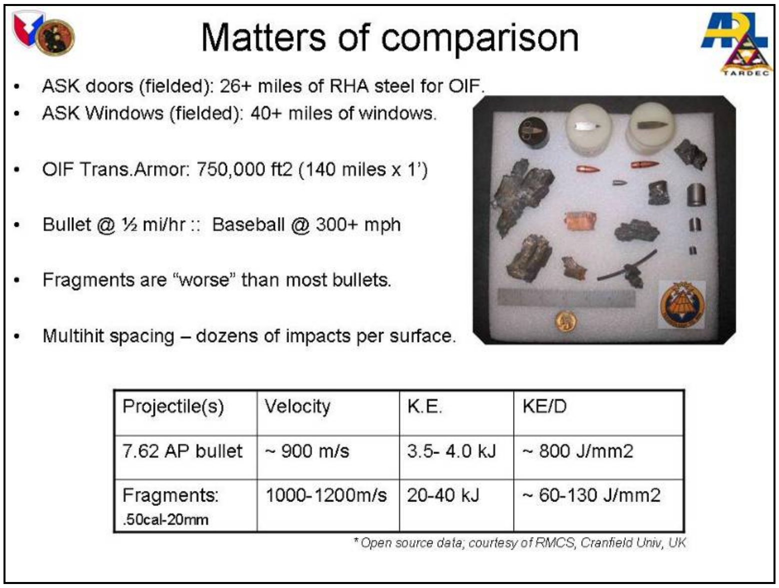


Figure 91. Despite development in technology, threats evolve as well.

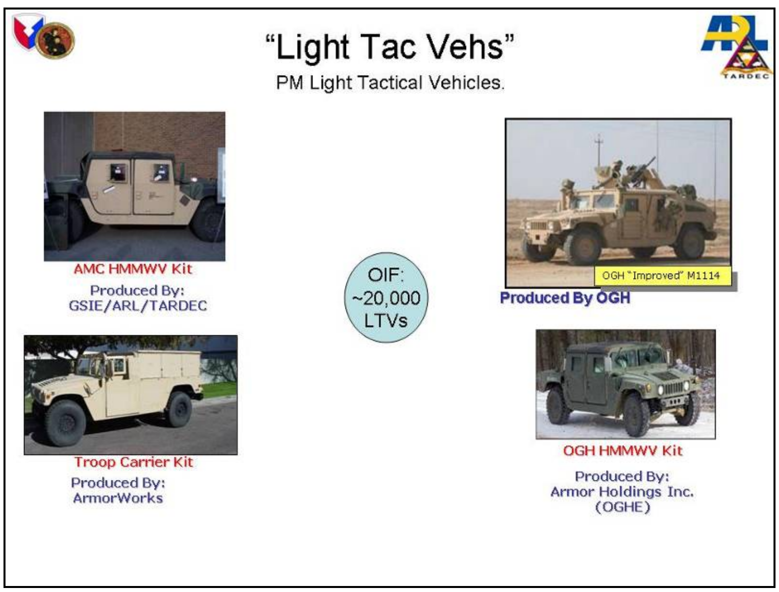


Figure 92. Theater vehicles have evolved due the threats.

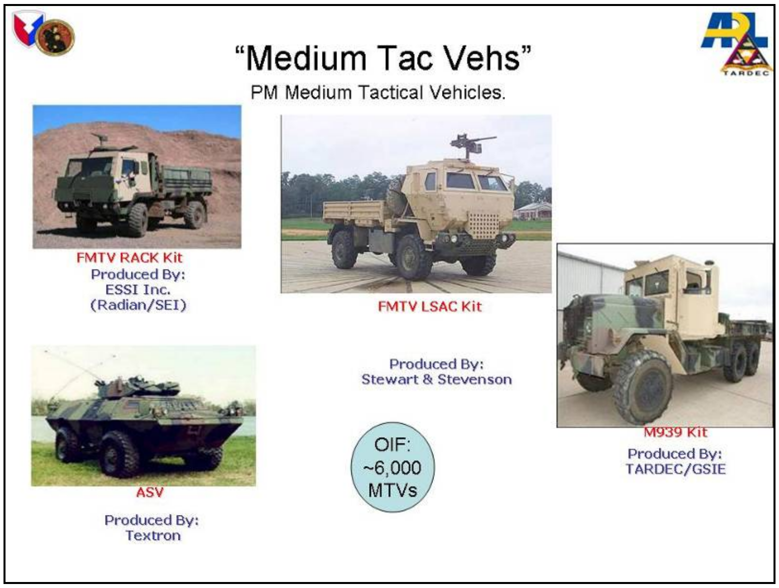


Figure 93. Future evolutions of protection are also in the development phases.

Figure 94. No vehicle is immune from armor needs due to the current theater environments of urban warfare.

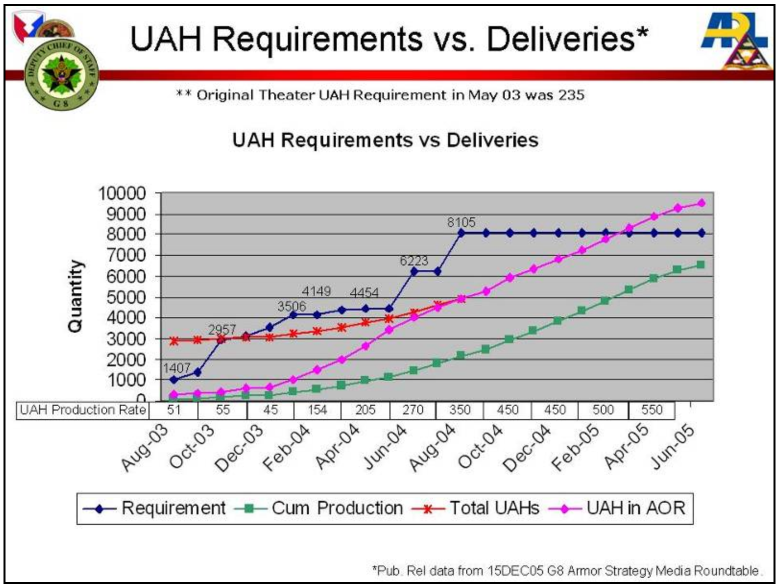


Figure 95. Armor requirements early on in the conflict as provided to public.

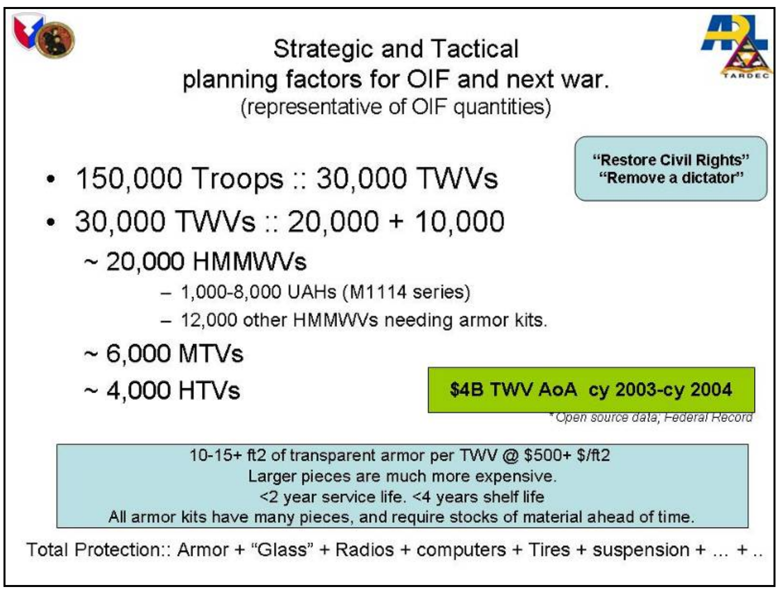


Figure 96. How much does all this technology cost? Technology costs are significant when putting the technology on thousands of platforms.

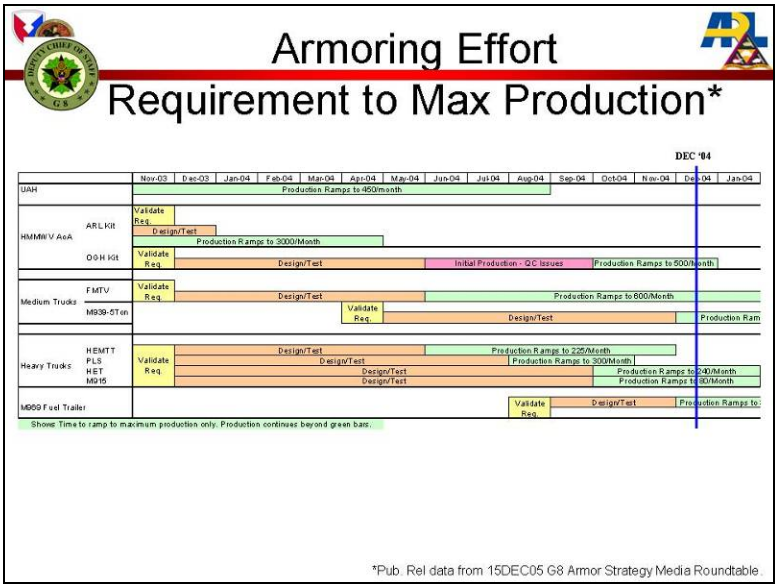


Figure 97. Rate of response for the U.S. Government to supply the best technologies available was rapid and included infrastructure and deployment requirements.

Figure 98. Even during deployments, the technology was advancing.

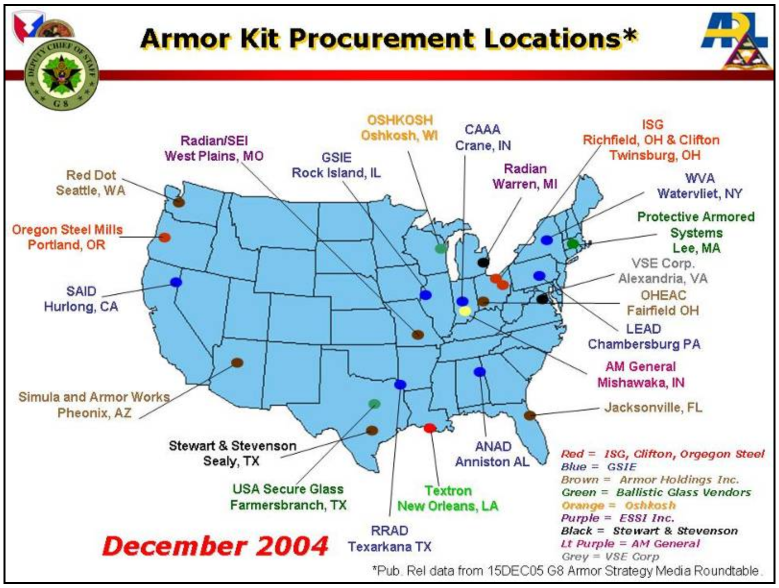


Figure 99. The whole country was involved in deploying protection technologies to the warfighter.

Figure 100. The technical know-how and the ability to deploy solutions rapidly resulted in many faces of the technology in theater.

Figure 101. The armor deployment strategy involved multiple phases for maximizing impacted personnel and platforms.

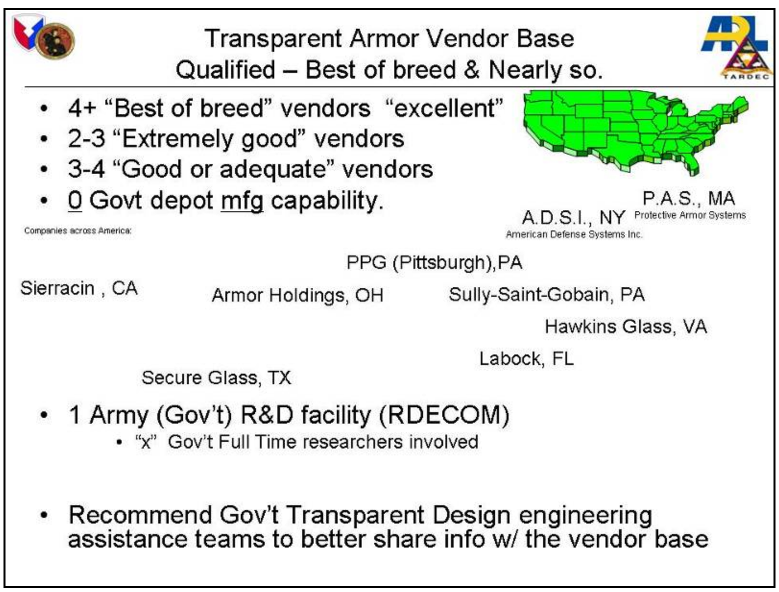


Figure 102. Transparent armor was also a critical insertion technology.

Figure 103. The Soldiers have first-hand experience with the protection capabilities and the importance of armored windows for the vehicles.

Figure 104. Transparent armor protection must be equivalent or better than the opaque solutions.

Figure 105. Transparent armor will be subjected to fragments and bullets of varying sizes.

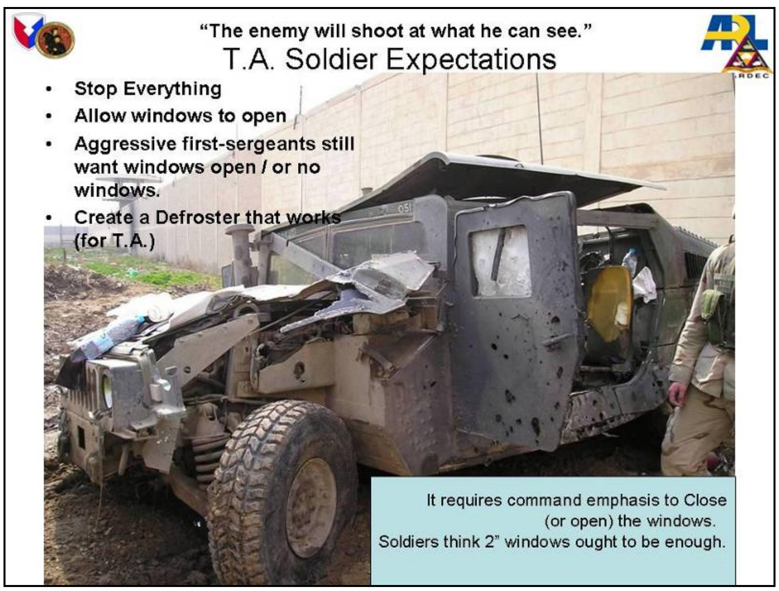


Figure 106. The enemy will shoot what it can see, so the Soldier expects the best available protection.

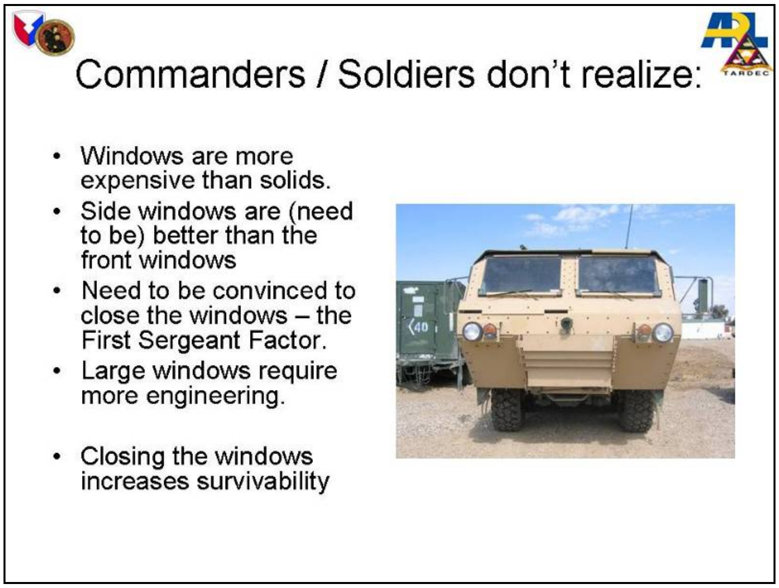


Figure 107. When in comes to economics, the Soldiers are not always aware of the commercial limitations behind what they know exists.

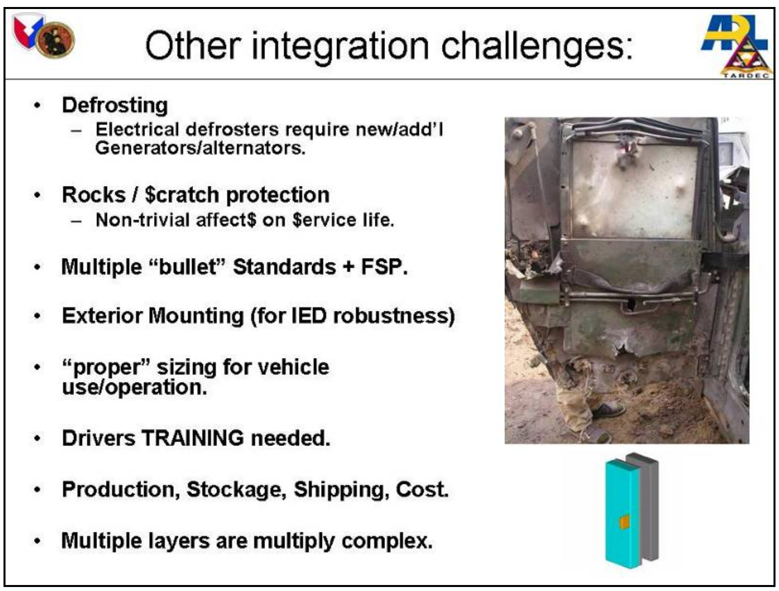


Figure 108. Integration is far more complex as armor sizes increase.

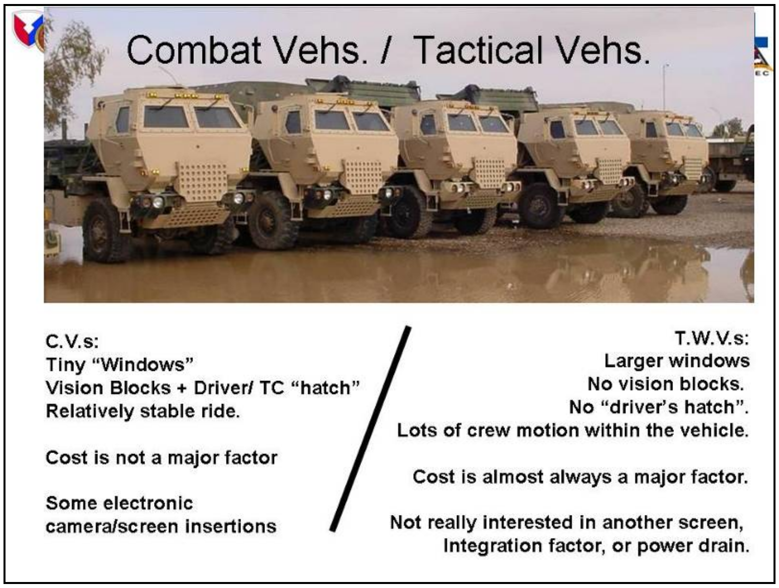


Figure 109. There is a significant difference between a tactical vehicle and a combat vehicle in regards to window dimensions.

Figure 110. Field feedback is essential to providing future designs that meet the needs.

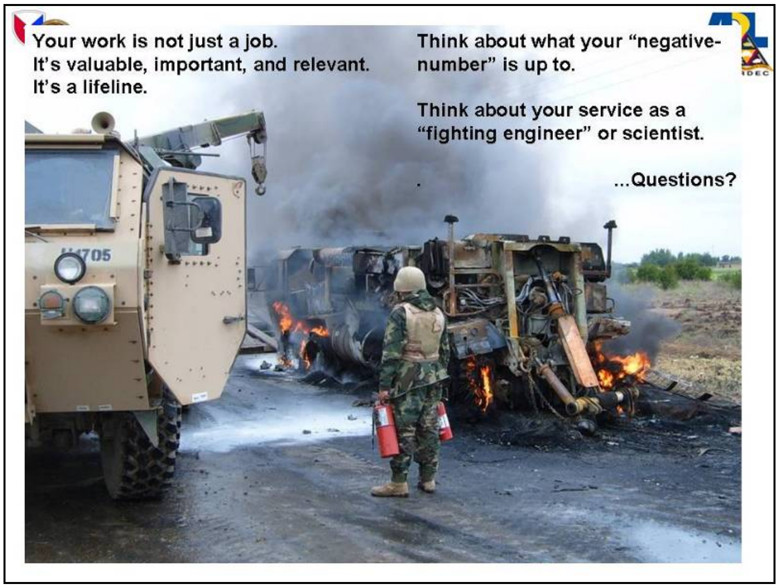


Figure 111. Soldier praise and encouragement that technology is important and makes a difference.

Figure 112. The major encourages being in touch with the Soldier via available communications to develop technologies for impact.

Figure 113. Sometimes the vehicle is lost, but a Soldier saved is worth the price.

7.4 The Challenges of On-The-Move Satellite Communications

Louis A. Coryell, U.S. Army CERDEC, Fort Monmouth, NJ 07703

Abstract of Briefing: The Army is pursuing technologies to meet transformation goals of a lighter, faster, more lethal force with integrated on-the-move communications from sensor to shooter. Affordable SATCOM antennas provide the means for this high data rate, beyond line of sight, on-the-move communications. This paper presents the evolution of mobile SATCOM antenna systems. Details are presented on both phased array and dish antenna systems and associated technologies. The need for antenna radomes to provide ballistic protection for SATCOM antennas is then discussed. Ballistic radome design considerations are given and materials issues are discussed. The presentation is shown as figures 114–139.

Figure 114. Dr. L. Coryell provided a briefing on importance of communications in the current and future Army tactics.

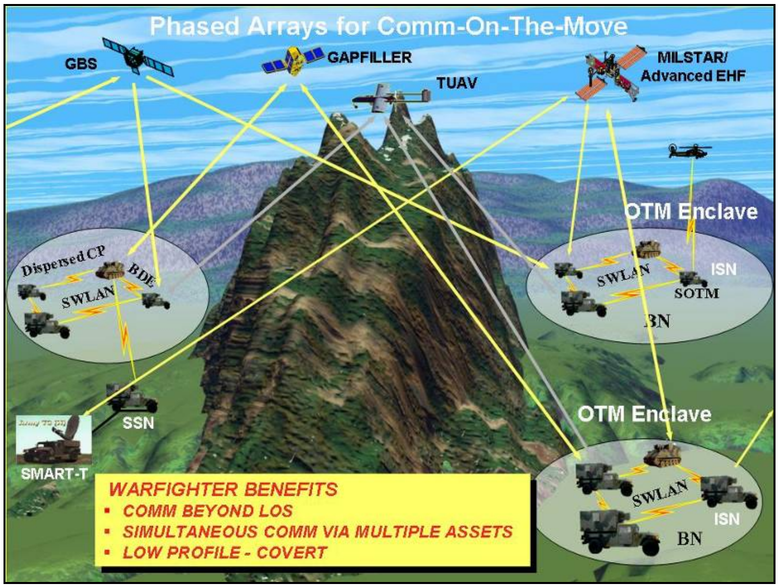


Figure 115. Communications is a key to successfully completing a mission with maximum effectiveness.

Figure 116. Communications on the move (COTM) has been a development area for some years.

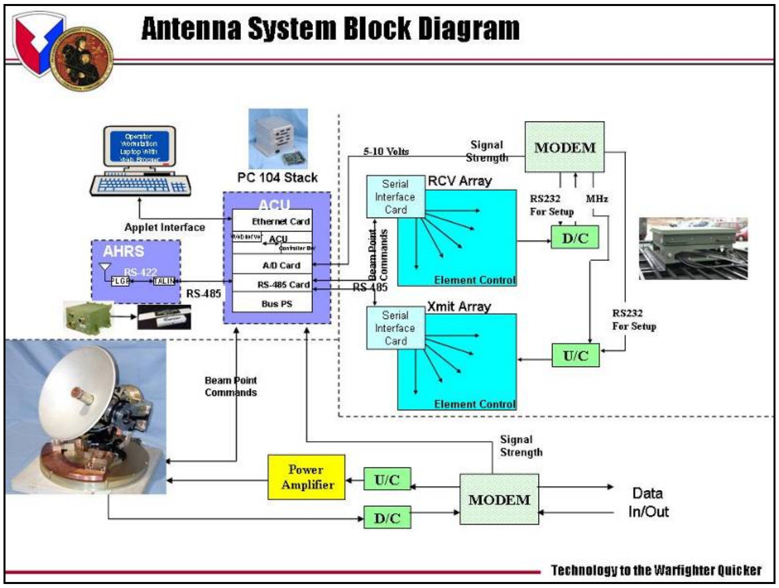


Figure 117. Antennae are critical to the communications network.

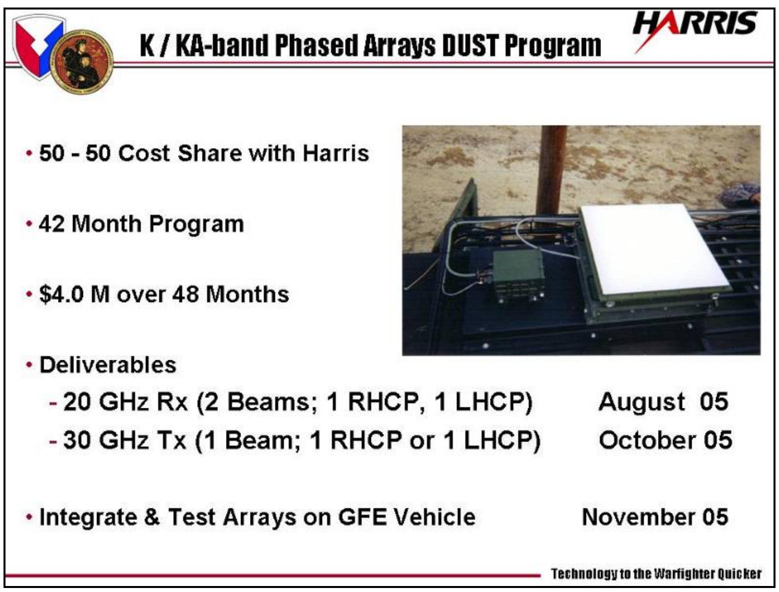


Figure 118. Cost reductions and technology enhancements are focuses of research efforts.

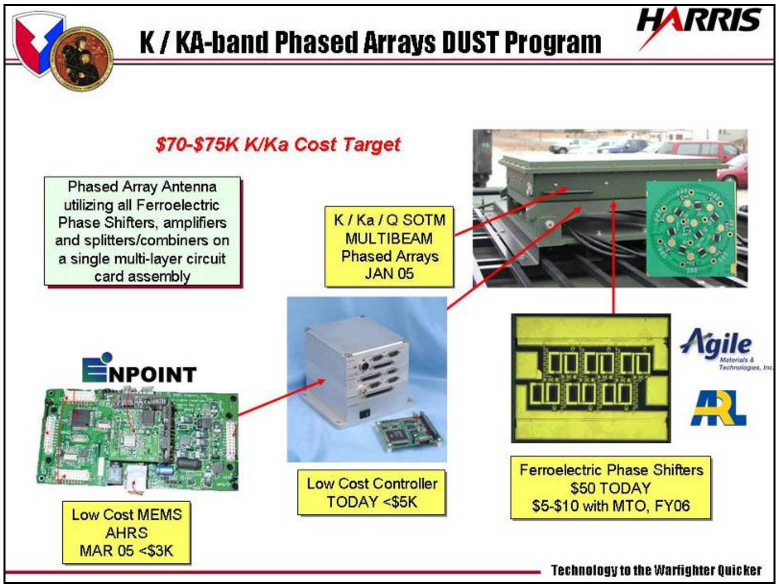


Figure 119. Testbed platforms are often significantly larger than what can effectively be deployed on platforms.

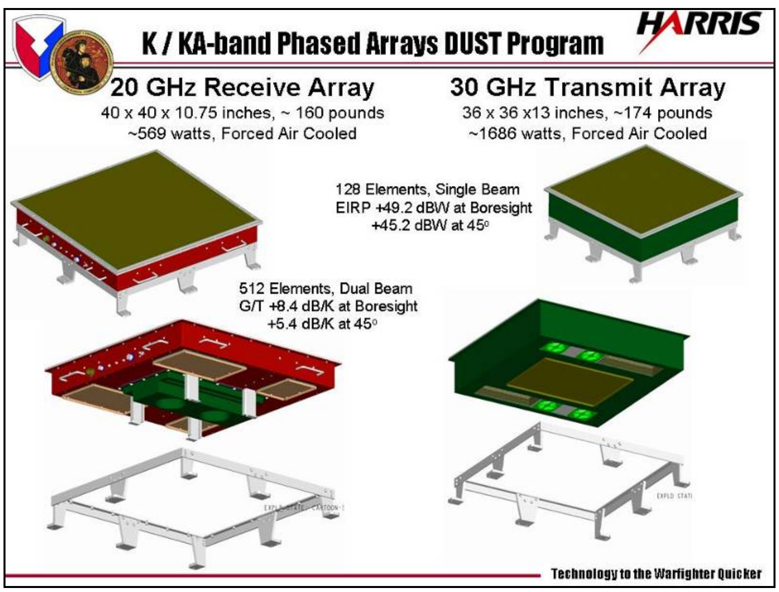


Figure 120. The introduction of commercial off the shelf technologies can help to reduce both size and costs of communications platforms.

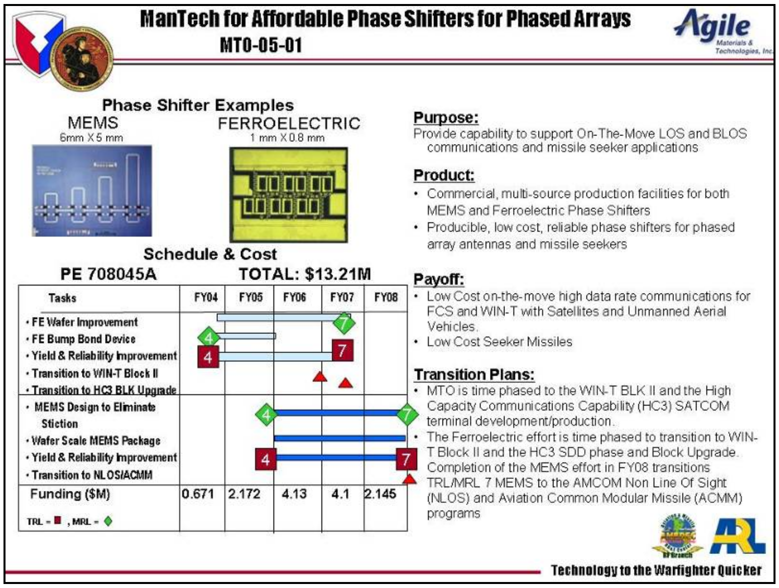


Figure 121. The Army continues to fund critical technologies that offer cost, power, and weight savings to the communications network.

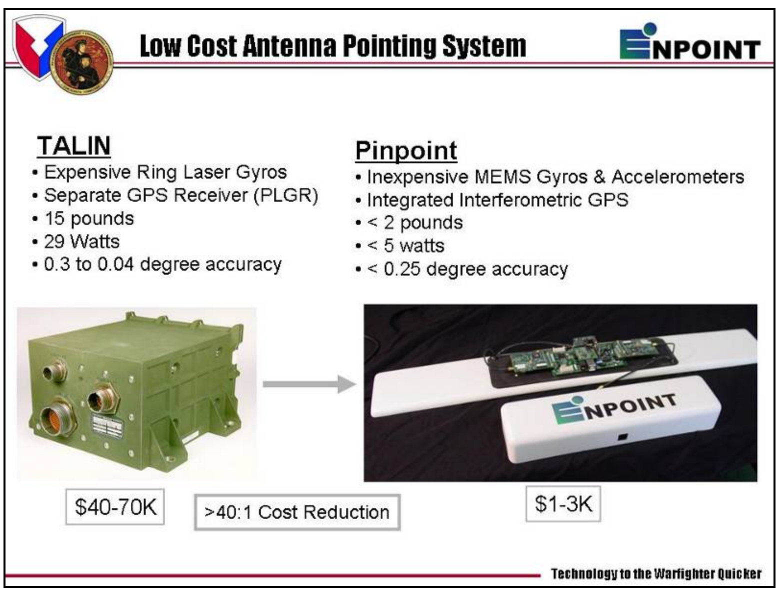


Figure 122. An example of the Army innovations that resulted in significant benefits in antennae development.

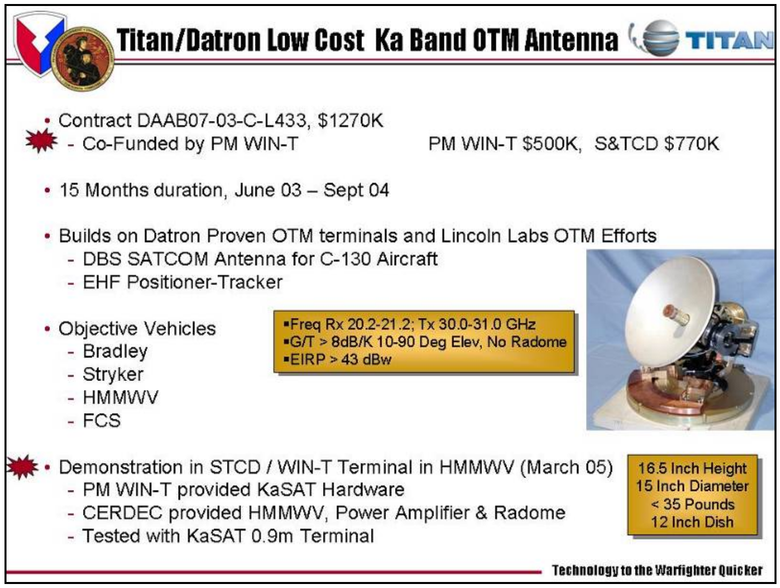


Figure 123. An additional technological advancement that enhances fielding opportunities by reducing size and cost of communications platforms.

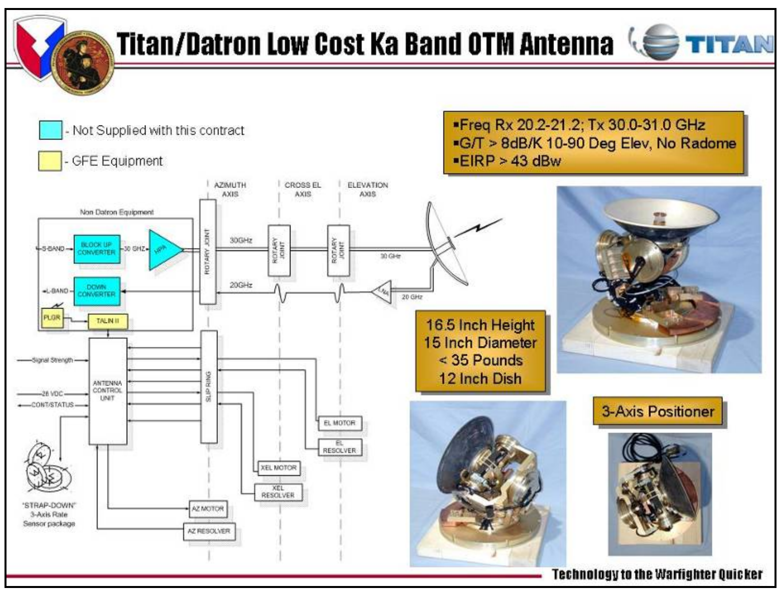


Figure 124. The Tritan/Datron communication antenna in essence.

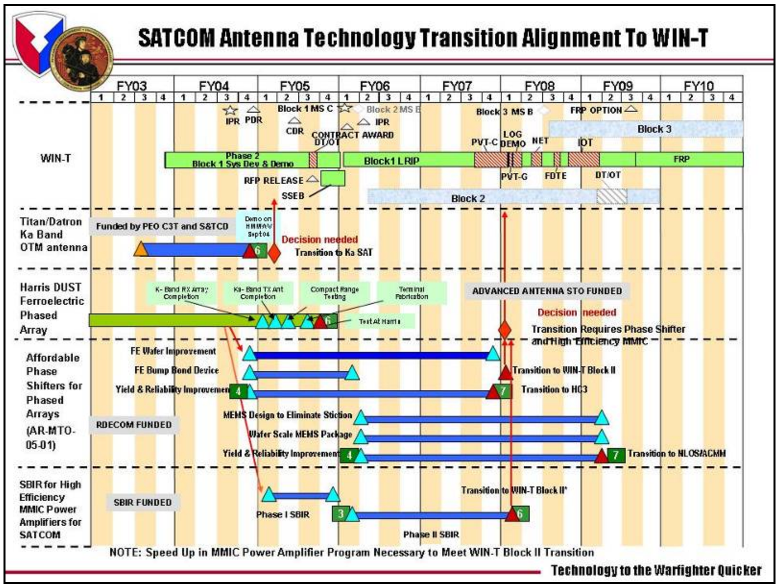


Figure 125. Timelines for technology delivery are short and opportunities for deployment are nearing.

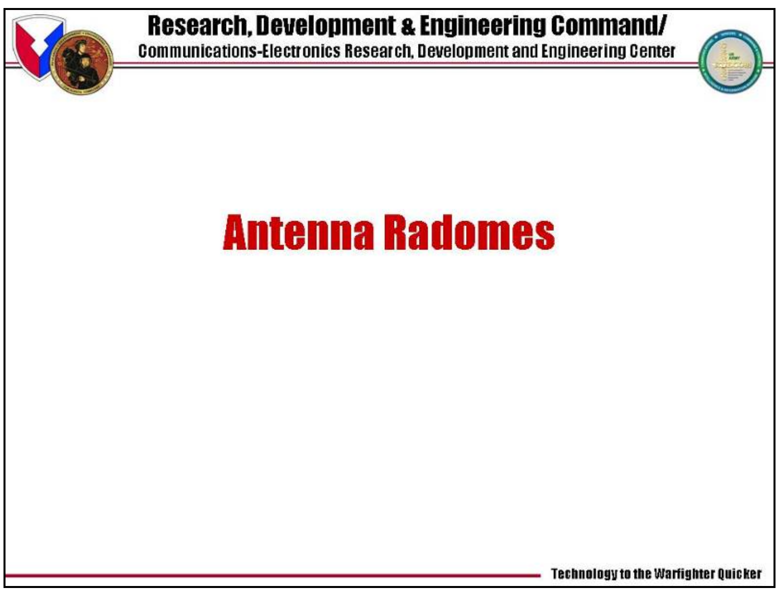


Figure 126. Protecting antennae is a critical need for the future designs.

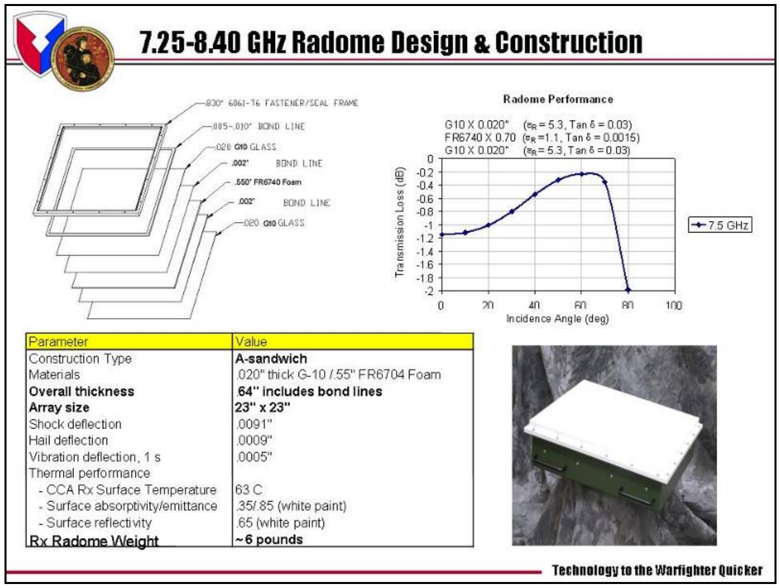


Figure 127. Complex protection schemes offer both weight and performance benefits.

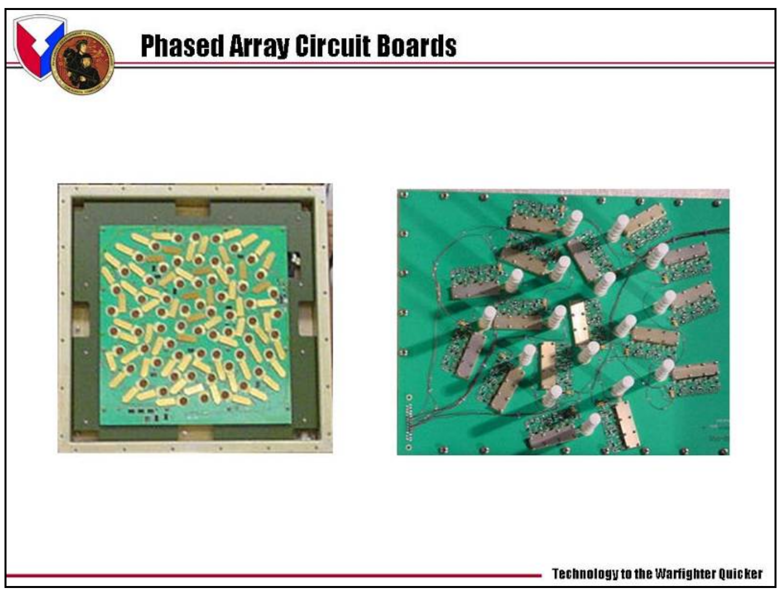
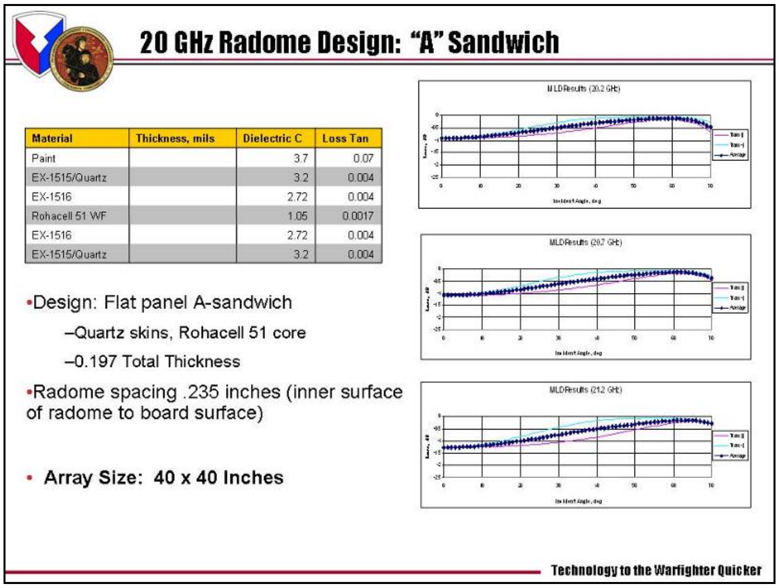
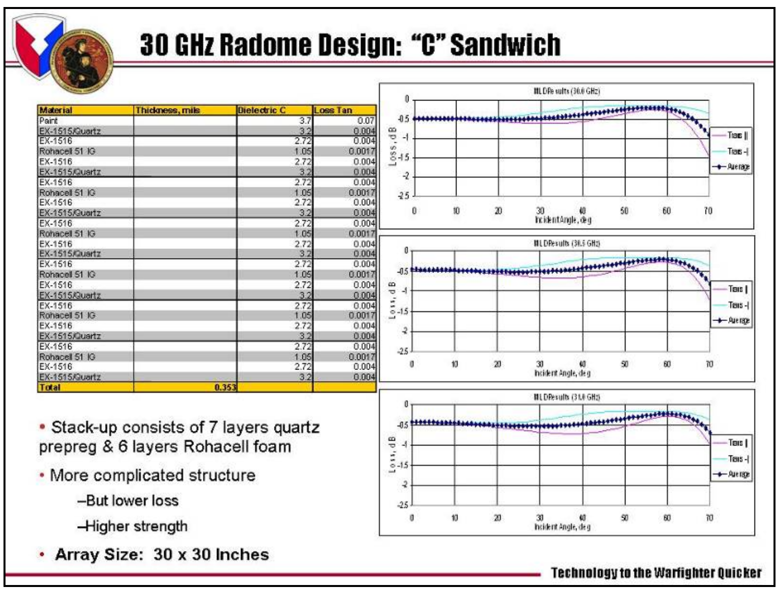


Figure 128. The electronics are complex and sensitive.



Material	Thickness, mils	Dielectric C	Loss Tan
Paint		3.7	0.07
EX-1515/Quartz		3.2	0.004
EX-1516		2.72	0.004
Rohacell 51 WF		1.05	0.0017
EX-1516		2.72	0.004
EX-1515/Quartz		3.2	0.004

Figure 129. Protection schemes also have transmission requirements for the antenna making them very difficult to engineer independently.



Material	Thickness, mils	Dielectric C	Loss Tan
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EX-1515/Quartz		3.2	0.004
EX-1516		2.72	0.004
Rohacell 51 IG		1.05	0.0017
EX-1516		2.72	0.004
EX-1515/Quartz		3.2	0.004
EX-1516		2.72	0.004
Rohacell 51 IG		1.05	0.0017
EX-1516		2.72	0.004
EX-1515/Quartz		3.2	0.004
Total	0.353		

Figure 130. Frequency dependence is also critical in radome design.

Figure 131. The size of the circuitry produces significant special protection needs. The circuits cross multiple layers, creating complex three dimensional stacks.

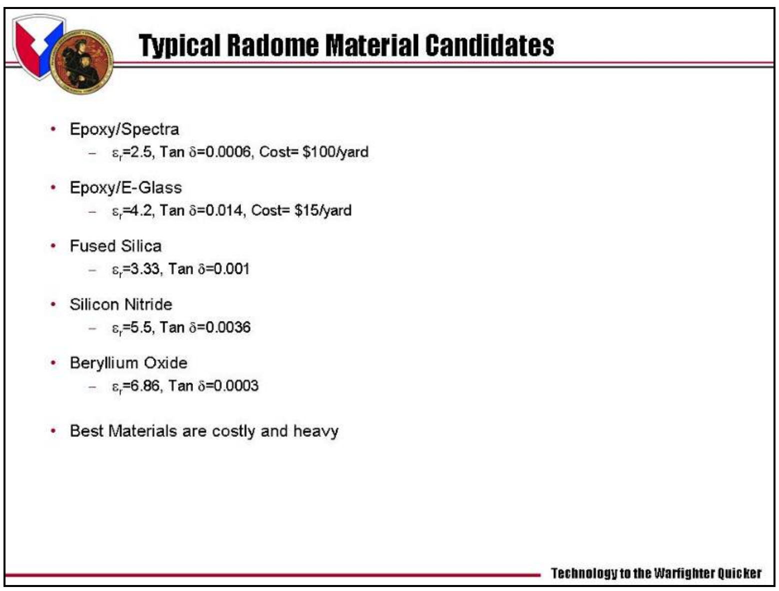

Figure 132. Material candidates used in radomes are typically low loss materials, which are not as effective for ballistics.

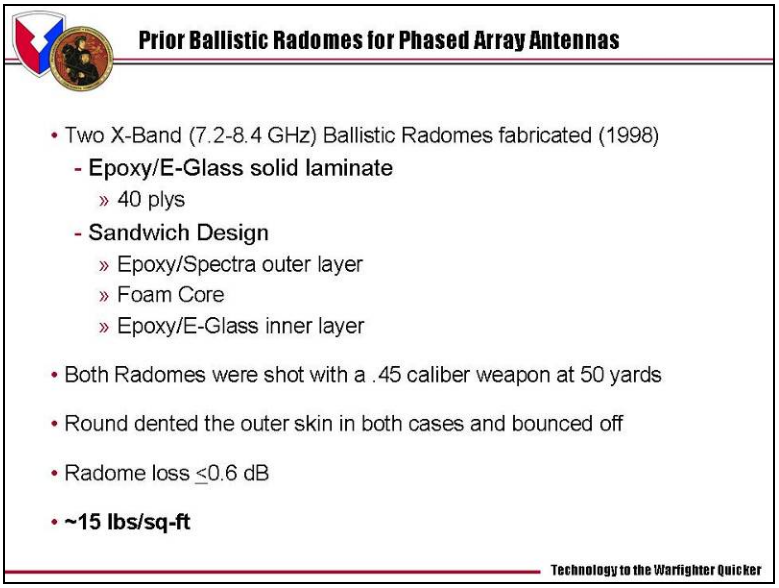

Figure 133. Previous research has offered some ballistic protection schemes for radomes in select frequency bands.

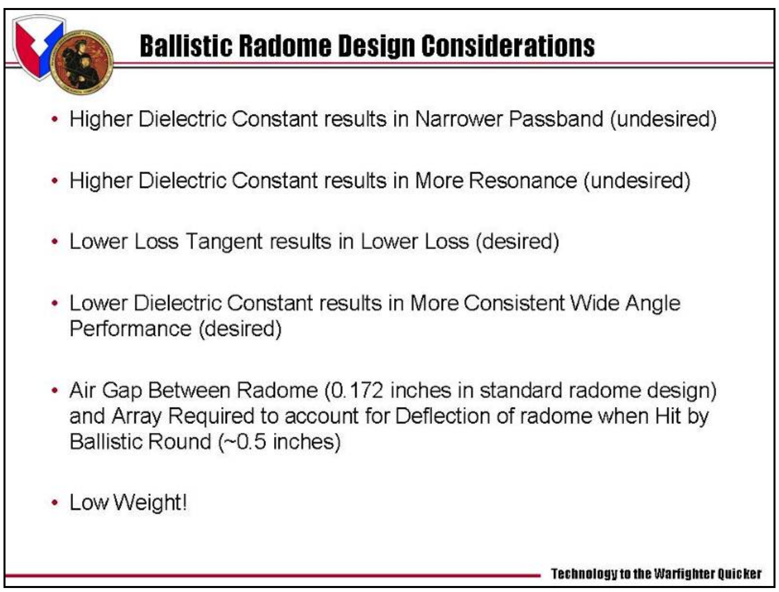

Figure 134. Some basic considerations for ballistic radome materials.

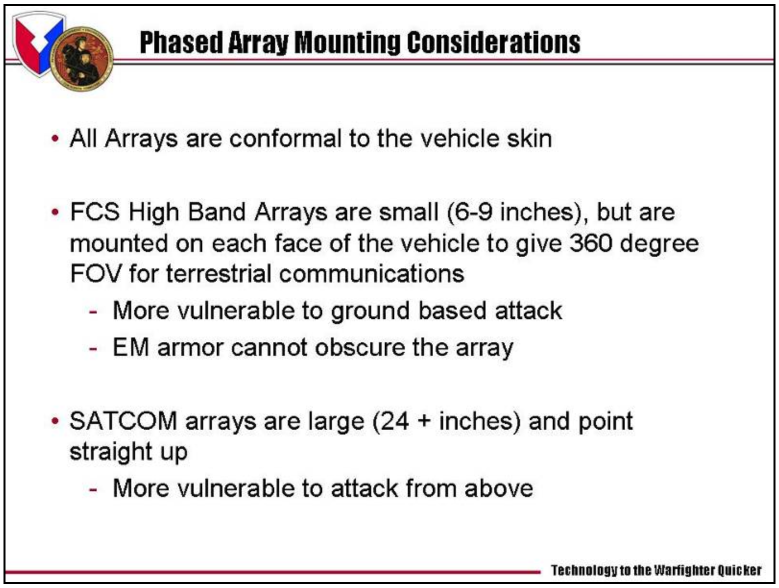

Figure 135. In addition to material needs, attachment needs and weight requirements are also important.

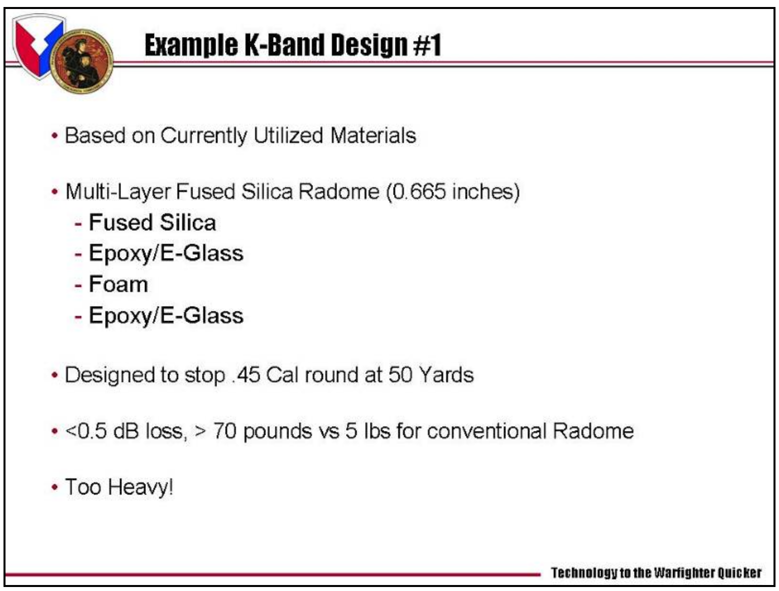

Figure 136. Some assembly options for K-band radomes and issues.

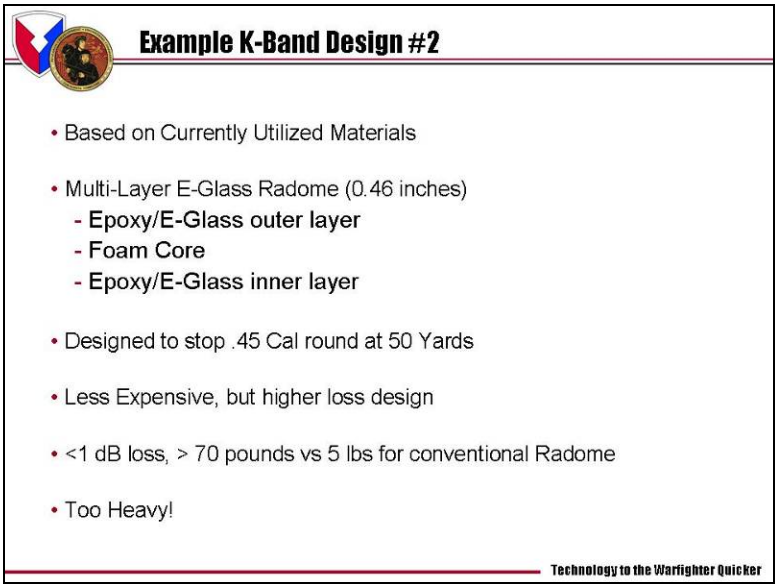

Figure 137. Another design for a radome and the issues.

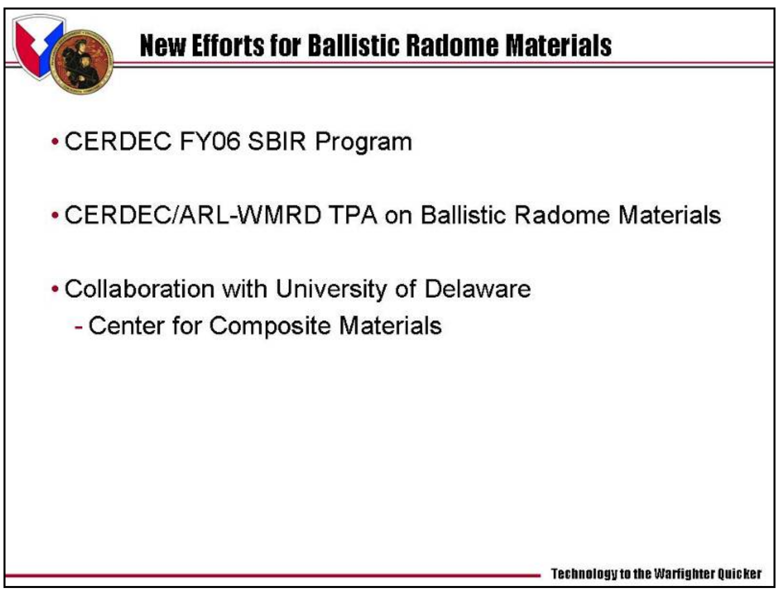

Figure 138. Efforts continue to pursue new technologies through commercial and academic partnerships.

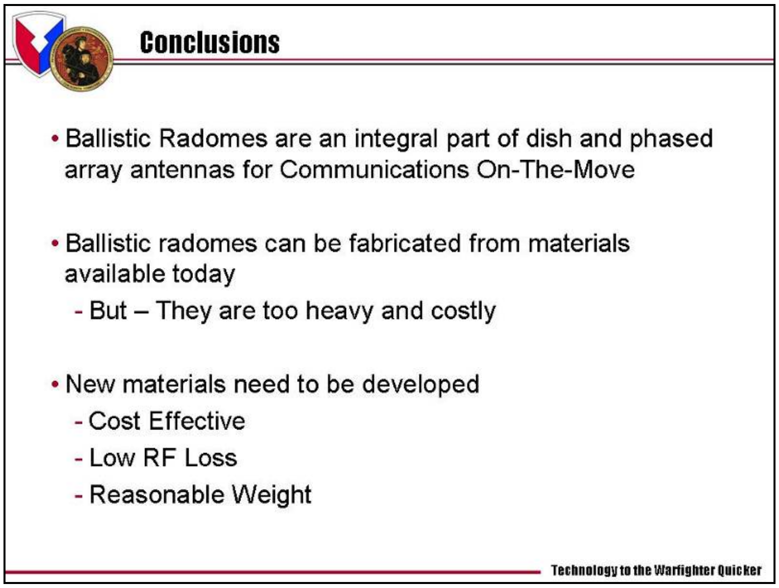

Figure 139. Conclusions of the presentation indicate that technology has a critical role to play in protecting sensor equipments.

7.5 Polycrystalline Materials for Laser Applications

Mr. Richard Gentilman, Raytheon Company, 350 Lowell Street, Andover, MA 01810

Abstract of Briefing: Laser quality polycrystalline materials, primarily YAG, have recently been commercialized by Konoshima Chemical Company in Japan. Raytheon and other organizations are also currently developing ceramic laser gain materials. Ceramic laser materials offer a number of performance and cost benefits over traditional single crystal materials. This presentation will compare state-of-the-art polycrystalline and single crystal laser materials, review recent laser demonstrations on Raytheon Yb: YAG ceramics, and summarize other on-going ceramic laser material development efforts in the United States.

Laser quality polycrystalline materials, primarily YAG, have recently been commercialized by Konoshima Chemical Company in Japan. Raytheon and other organizations are also currently developing ceramic laser gain materials. Ceramic laser materials offer a number of performance and cost benefits over traditional single crystal materials. This presentation will compare state-of-the-art polycrystalline and single crystal laser materials, review recent laser demonstrations on Raytheon Yb: YAG ceramics, and summarize other on-going ceramic laser material development efforts in the United States. The presentation is provided as figures 140–160.

Figure 140. Polycrystalline materials for laser applications.

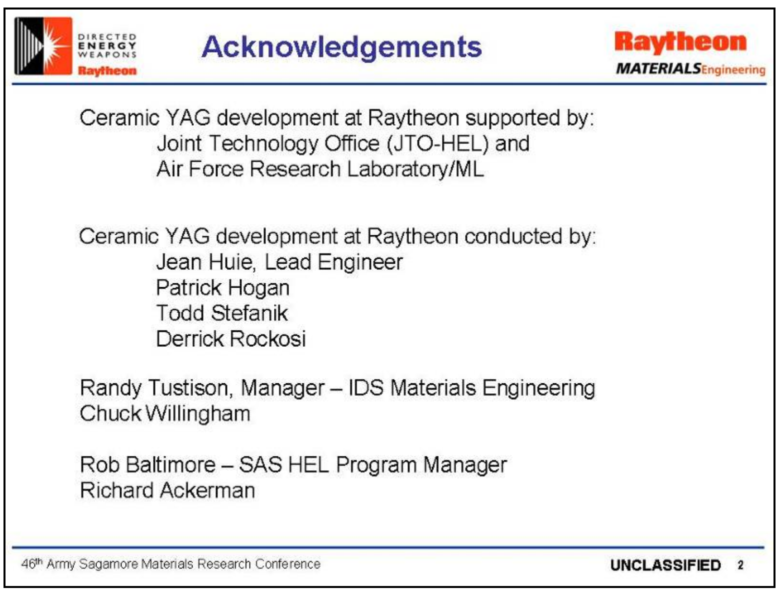

Figure 141. Acknowledgements.

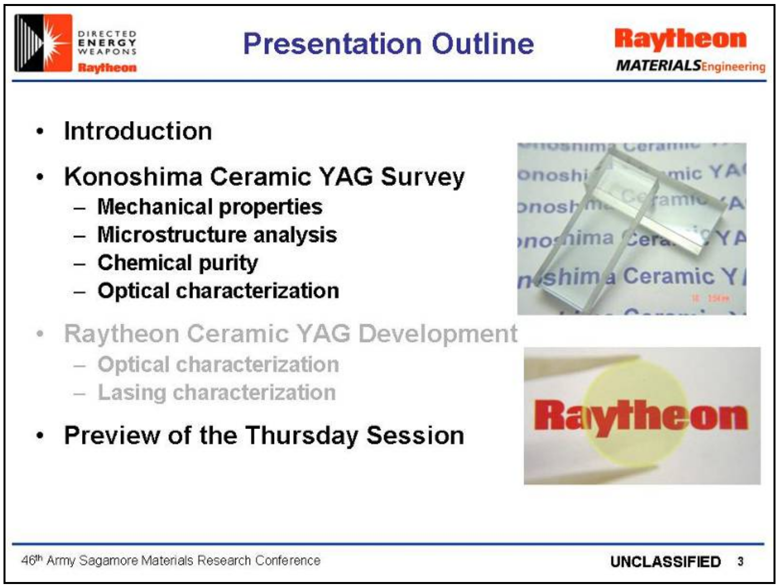

Figure 142. Presentation outline.

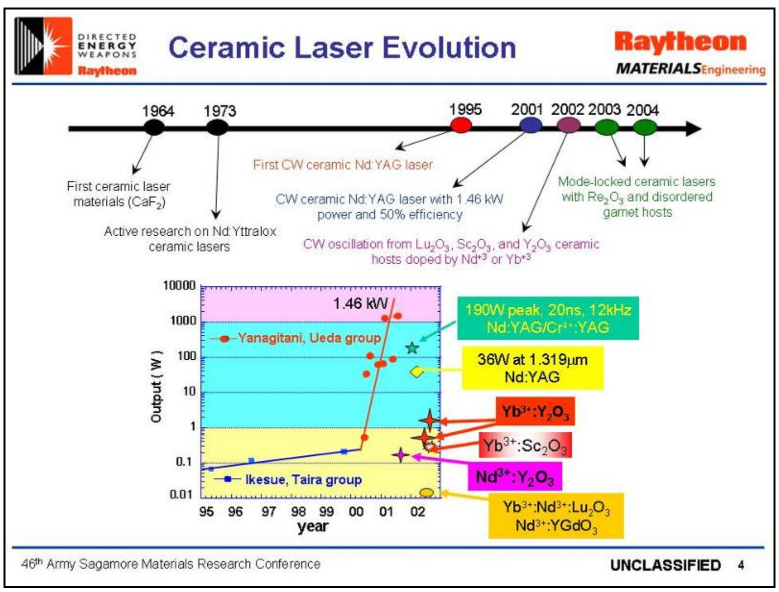

Figure 143. Ceramic laser evolution.

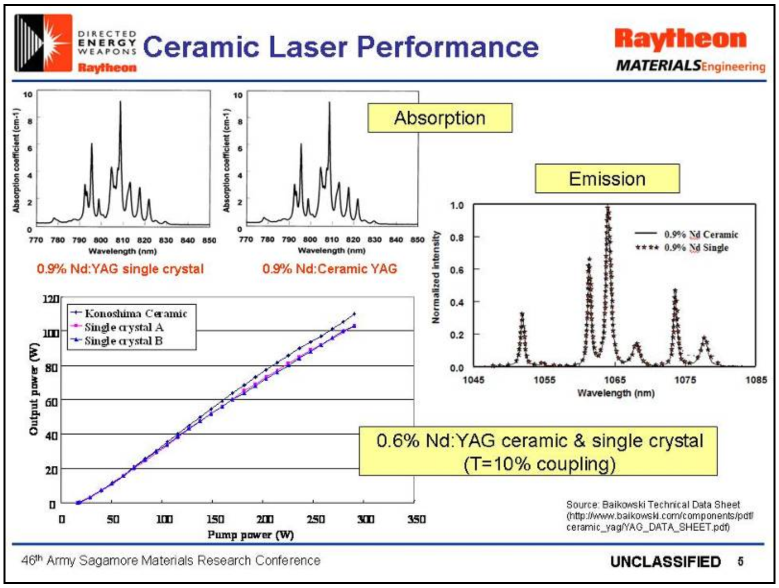

Figure 144. Ceramic laser performance.

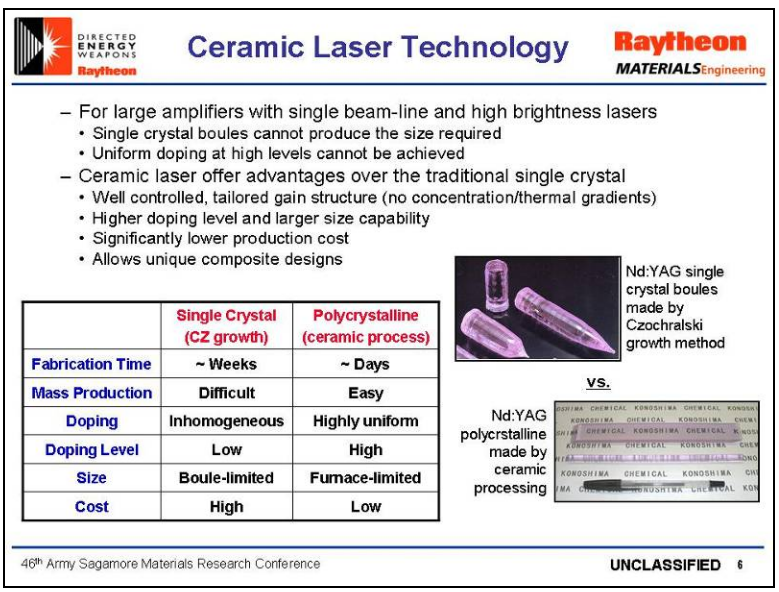

Figure 145. Ceramic laser technology.

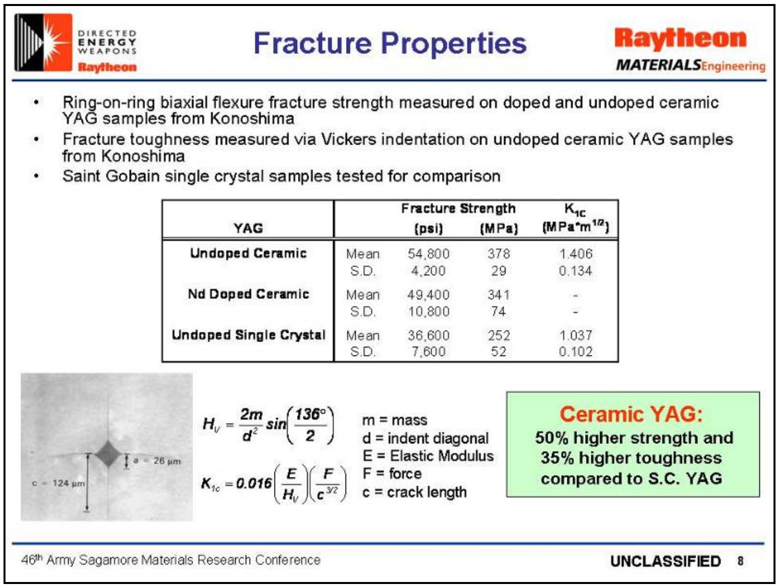

Figure 146. Fracture properties of laser ceramics.

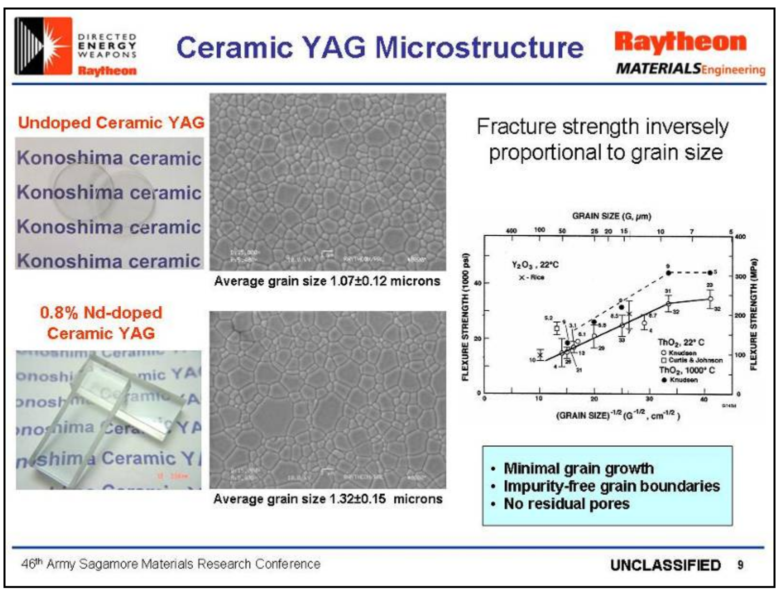

Figure 147. Ceramic YAG microstructure.

Chemical Purity Analysis

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Raytheon MATERIALS Engineering

Element	Konoshima Undoped PC YAG [ppm wt]	Saint-Gobain Undoped SC YAG [ppm wt]	Konoshima Doped PC YAG [ppm wt]
Li	0.65	0.35	< 0.05
Na	6.9	10	1.5
Mg	0.35	0.75	< 0.05
Si	50	2.5	15
P	0.55	< 0.05	0.35
S	0.65	0.35	0.25
Cl	1.1	1.5	0.09
K	0.75	0.35	0.15
Ca	1.5	0.33	1.5
Ti	0.23	0.45	0.15
Cr	0.55	1.3	10
Mn	< 0.05	< 0.05	< 0.05
Fe	1.1	1.1	0.23
Co	< 0.01	0.02	0.05
Ni	0.11	0.25	< 0.05
Zn	0.15	0.15	< 0.05
As	< 0.1	< 0.1	< 0.1
Zr	< 0.5	< 0.5	3.5
Sn	< 0.1	< 0.1	< 0.1
Ce	< 0.05	< 0.05	< 0.05
Nd	0.35	0.25	0.5 wt %
Yb	< 0.05	< 0.05	< 0.05
W	< 10	< 10	< 10
Ir	< 0.05	< 0.05	< 0.05
Pb	< 0.5	< 0.5	< 0.5

- Specific impurities can be:
  - **Deleterious**
  - **Beneficial**
  - **Neutral**
- Trace impurity analysis via Glow Discharge Mass Spectrometry (GDMS)
- Scanned for 25 elements
- Konoshima ceramic YAG has exceptional chemical purity -- equivalent to that of CZ grown single crystal
- Silica found in 10's of ppm

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Figure 148. Chemical purity analysis.

Optical Characterization

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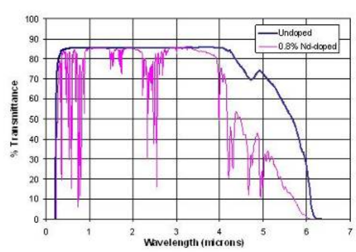
Raytheon MATERIALS Engineering



- **2.5 mm thick Konoshima undoped ceramic YAG has 84% theoretical transmission from ~350 nm to ~4 μm**
- **High optical transparency supported by**
  - **Absence of impurities/inclusions**
  - **Fully dense without residual pores**
  - **Phase purity**

- **Absorption measurements via laser calorimetry at 940 nm and 1 kW of incident power**
- **Re-tested after a thermal anneal at 500°C**
- **Single crystal YAG samples from two different boules procured from Saint Gobain**
  - Order of magnitude variation
  - Sensitive to the state of anneal
- **Further testing with larger sample set ongoing**

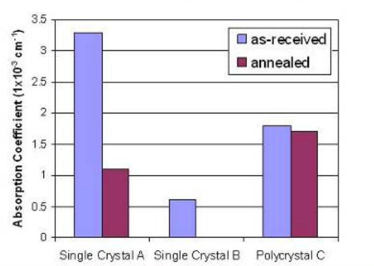


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Figure 149. Optical characterization of ceramics.

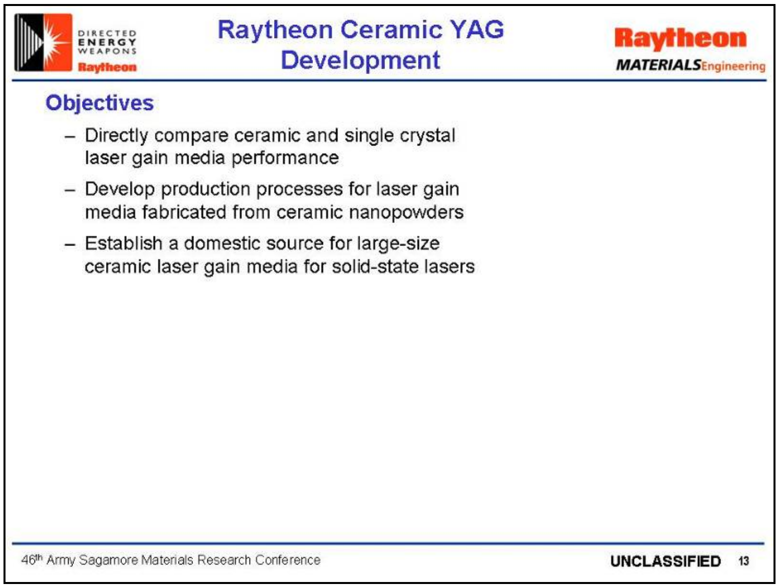

Figure 150. Raytheon ceramic YAG development.

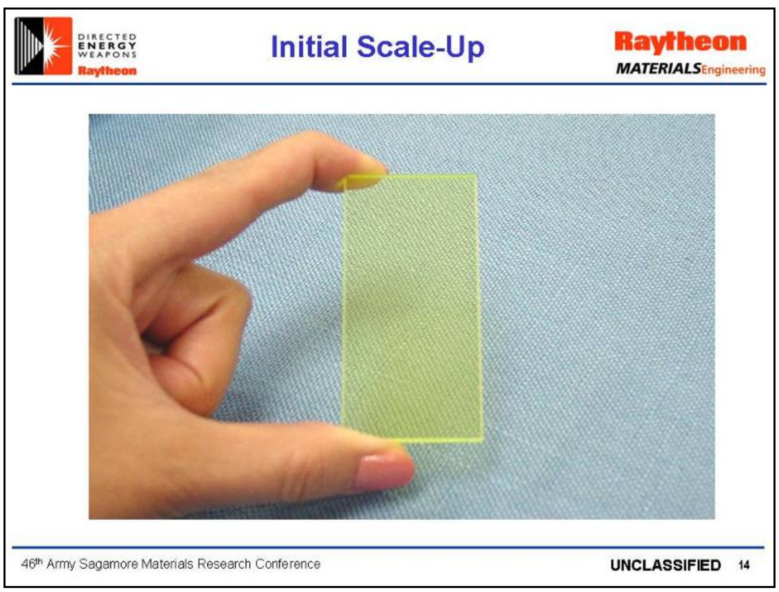

Figure 151. Initial scale-up of ceramic YAG at Raytheon.

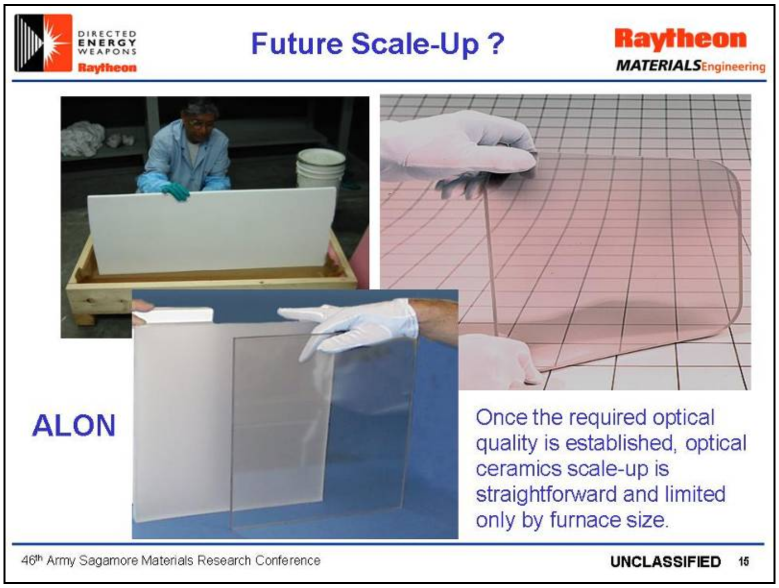

Figure 152. Other scale-up efforts at Raytheon.

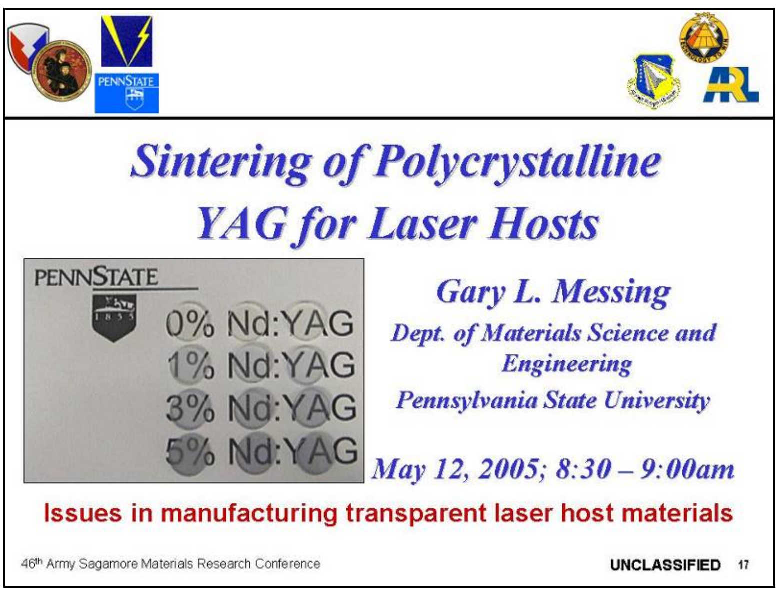

Figure 153. Preview slide showing sintering efforts in YAG for laser hosts.

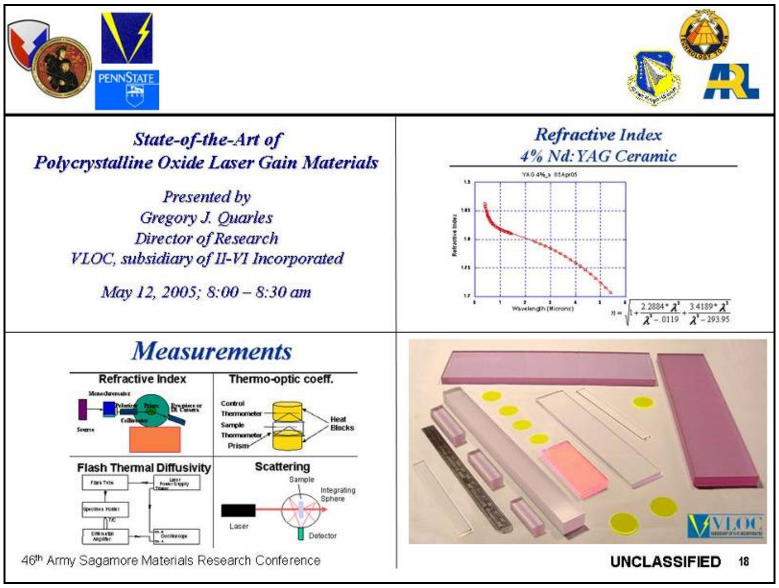

Figure 154. Preview slide showing sintering efforts in YAG for laser hosts.

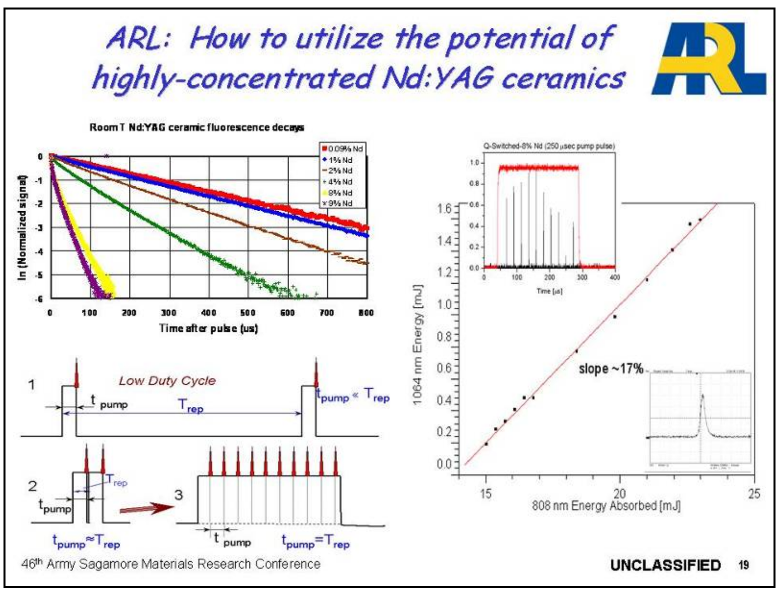

Figure 155. Preview slide showing sintering efforts in YAG for laser hosts.

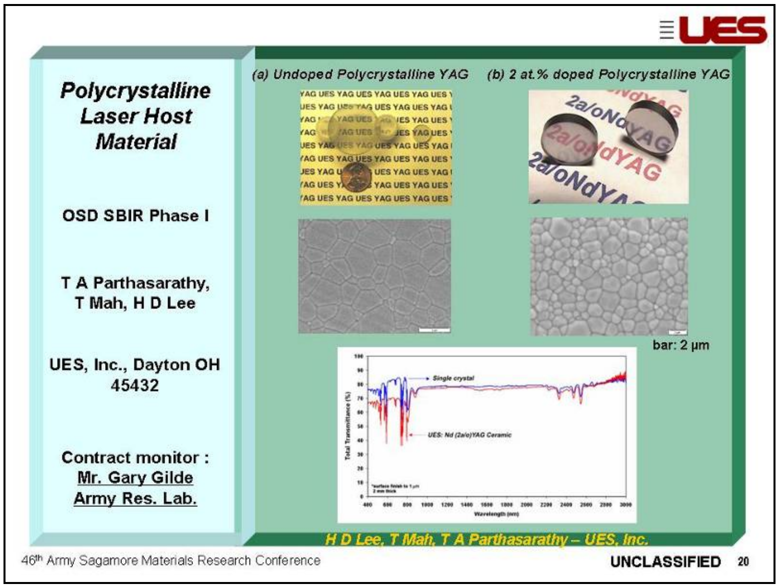

Figure 156. Preview slide showing sintering efforts in YAG for laser hosts.

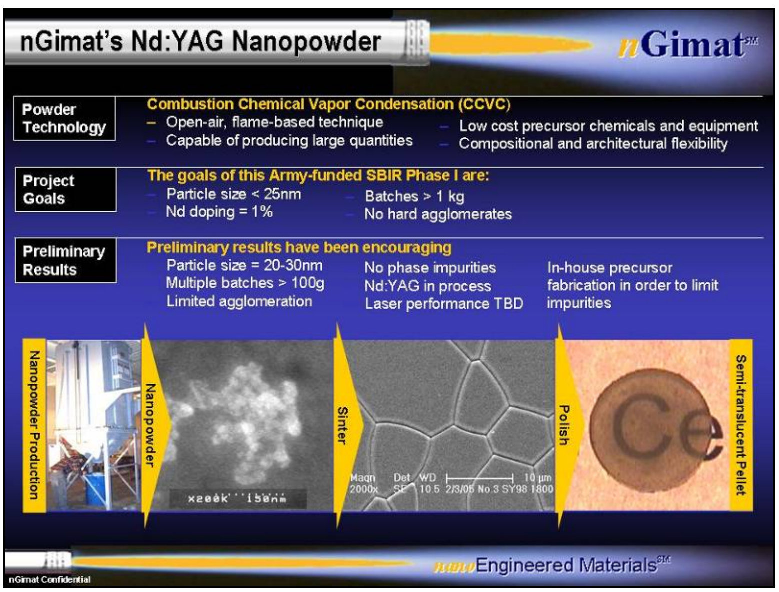

Figure 157. Preview slide showing sintering efforts in YAG for laser hosts.

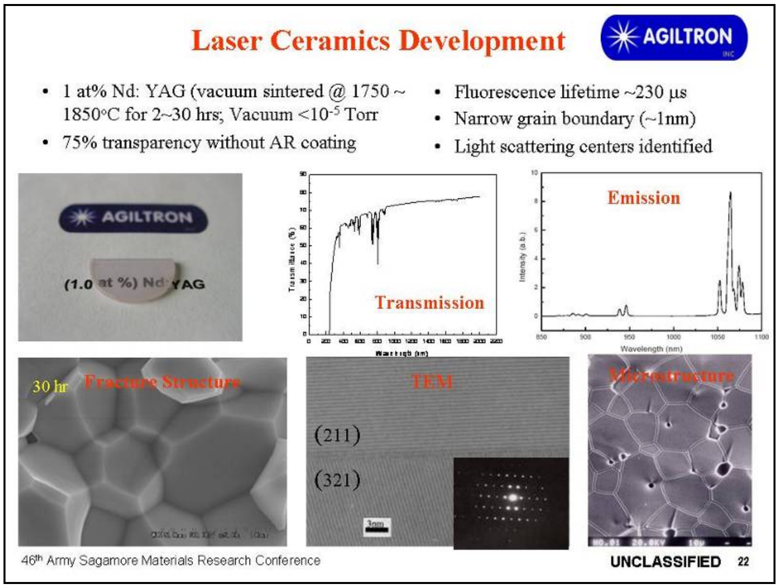

Figure 158. Preview slide showing sintering efforts in YAG for laser hosts.

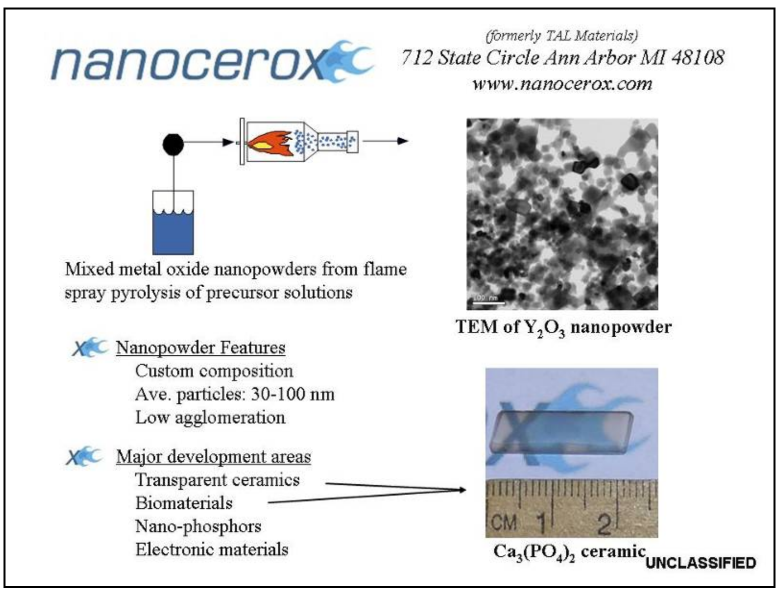

Figure 159. Preview slide showing sintering efforts in YAG for laser hosts.

Figure 160. Summary and conclusions.

7.6. Advances and Needs in Multi-Spectral Transparent Materials Technology

Dr. Daniel Harris, U.S. Navy, China Lake, CA

Abstract of Briefing: Dr. Daniel Harris is a leading expert in the development of transparent materials for sensor protection in rocket and missile technology. Since the environment for missiles and rockets involves extreme thermal loading and thermal shock conditions, in addition to highly abrasive environments that result from particles of sand and water in the atmosphere, sensors for missile applications demand very high performance materials. Additionally, the optical requirements for these sensors are exceptionally challenging to achieve. Sensor systems must be able to look through the radomes without loss of targeting capability, which means flaws must be exceptionally well-defined and minimally impact the field of view. Dr. Harris provides a brief summary of technology requirements as offers a number of technical approaches being explored to create next generation capabilities for multi-mode seekers. The presentation is offered as figures 161–189.

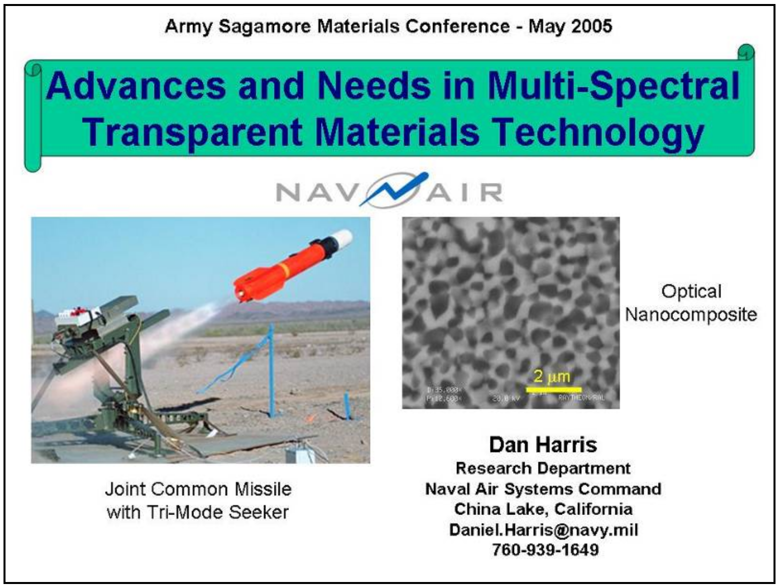

Figure 161. Joint Common Missile project needs briefing.

Figure 162. Zinc sulfide Maverick missile dome fractured due to rain impact.

Figure 163. Sidewinder dome with pitting erosion by sand.

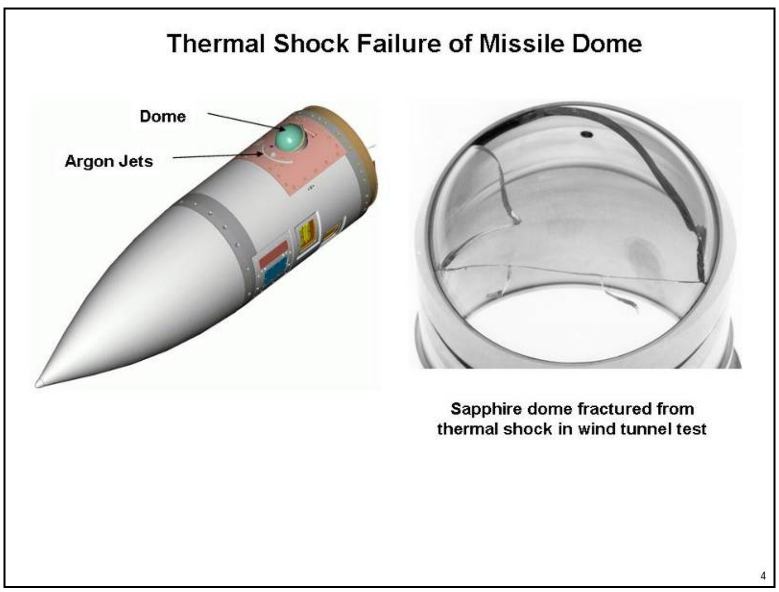

Figure 164. Thermal shock failure of a ceramic dome in wind tunnel.

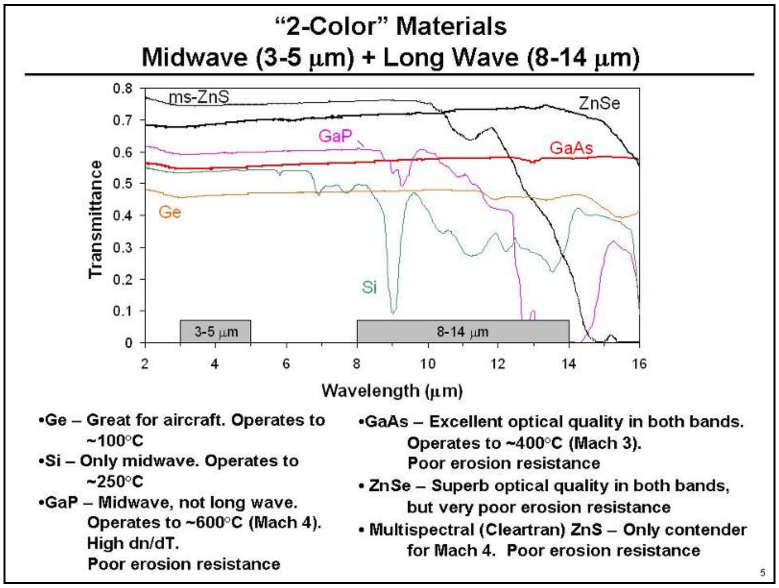

Figure 165. Multi-mode transmission issues with traditional dome materials.

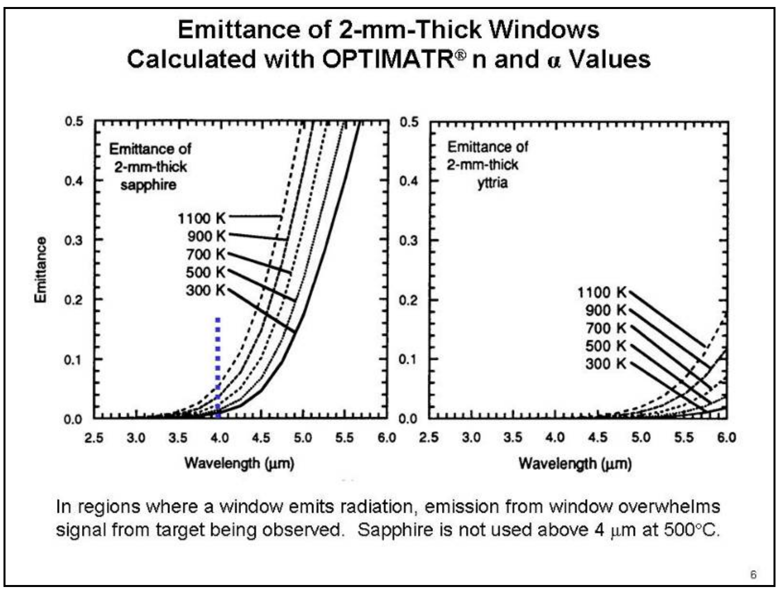

Figure 166. Emittance of windows based on commercial ceramics.

Microwave Dielectric Properties

INFRARED MATERIAL	DIELECTRIC CONSTANT	LOSS TANGENT
ZnS	8.35	0.0024
ZnSe	8.98	0.0017
ALON	9.28	0.00027
Spinel (35 GHz, 1987)	9.19	0.00022
Spinel (75-100 GHz, 2000)	8.37	0.002
Sapphire	9.39 (E⊥c)	0.00005
	11.58 (E||c)	0.00006
MgF_2	5.1	0.0001
CaF_2	6.5	0.00015
Calcium Aluminate	9.0	0.0025
Yttria	11.8	~0.0005
Lanthana-Doped Yttria	12.2	~0.0005
Diamond (Type IIa)	5.61	0.0006
GaAs	~12	~0.003
Si	~12	~0.009
RADOME MATERIAL		
Organic Composites	2-4	0.0001-0.01
Quartz-Polyimide	3.2	0.008
Pyroceram	5.58	0.0008
Duroid (Teflon)	2.65	0.003
Fused Silica	3.33	0.001
Silicon Nitride	5.50	0.003

RF dome is best if dielectric constant and loss tangent are both low

7

Figure 167. Dielectric properties of materials commonly used in dome applications.

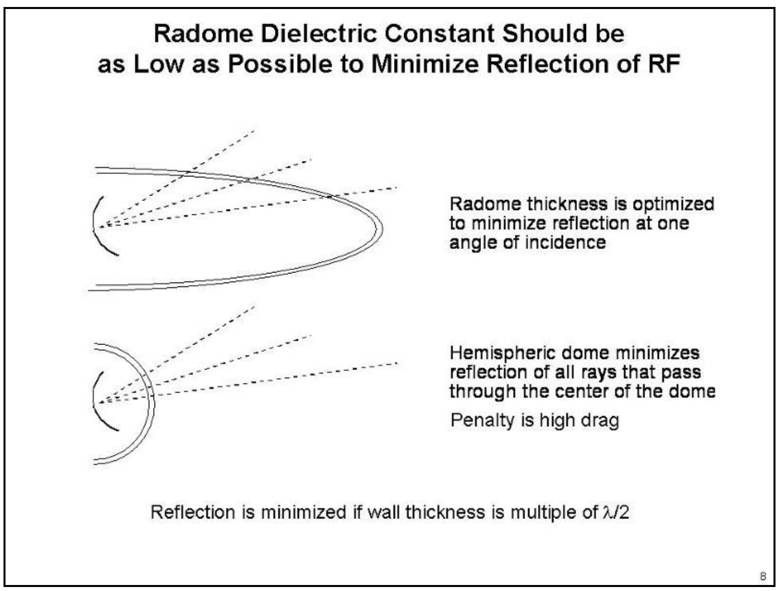

Figure 168. Effect of dielectric constant on line of sight in hemispherical and conical domes.

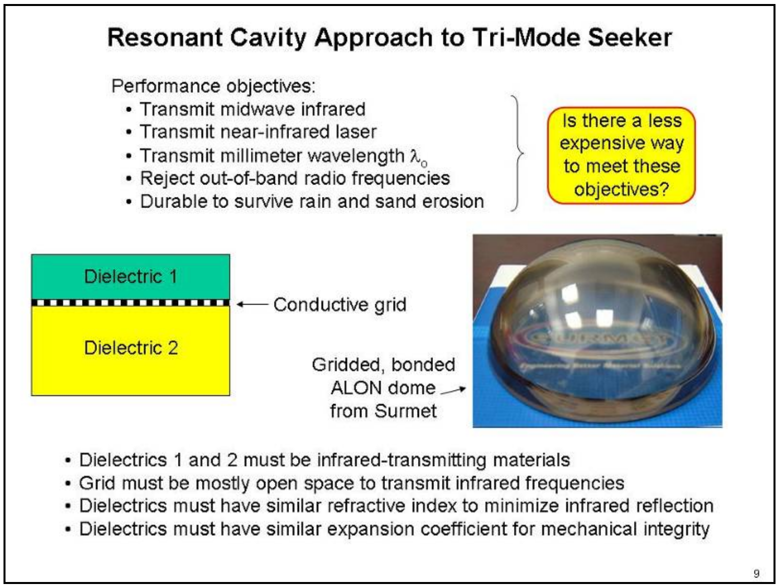

Figure 169. Resonant cavity approach to making a tri-mode seeker.

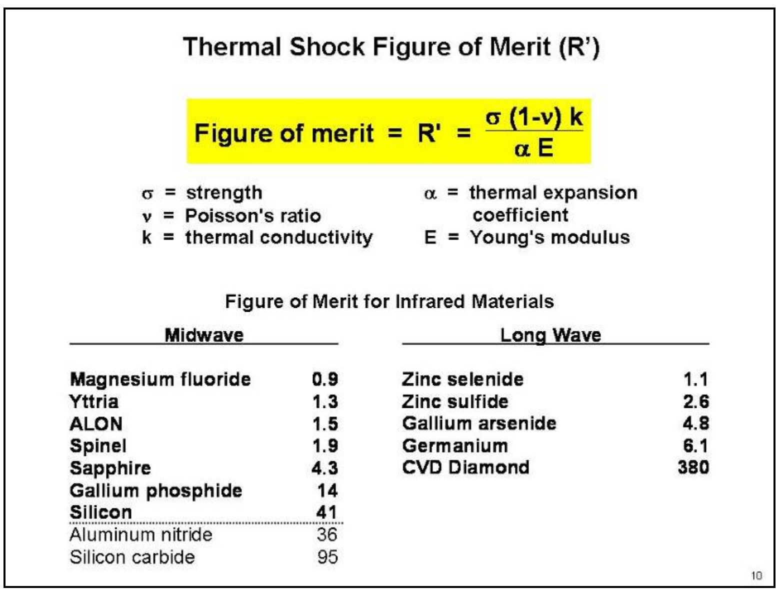

Figure 170. Thermal shock figure of merit computation for ranking new materials technologies.

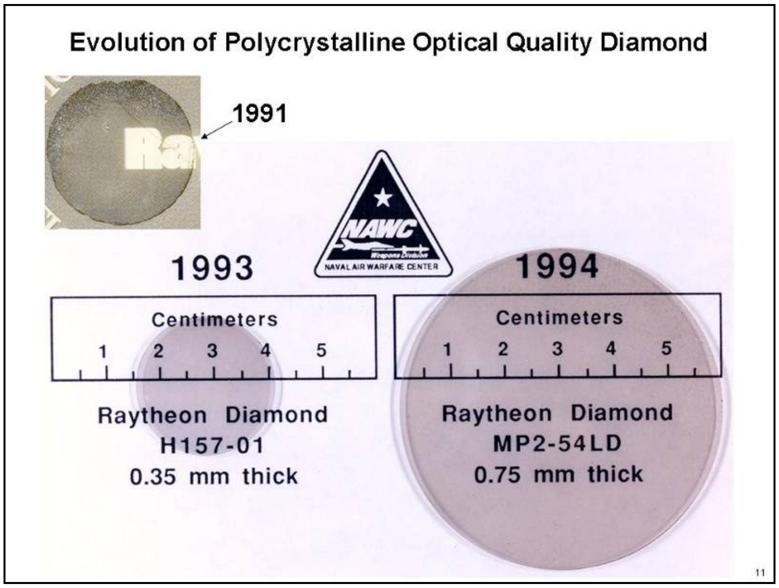

Figure 171. Evolution of polycrystalline optical quality diamond for domes.

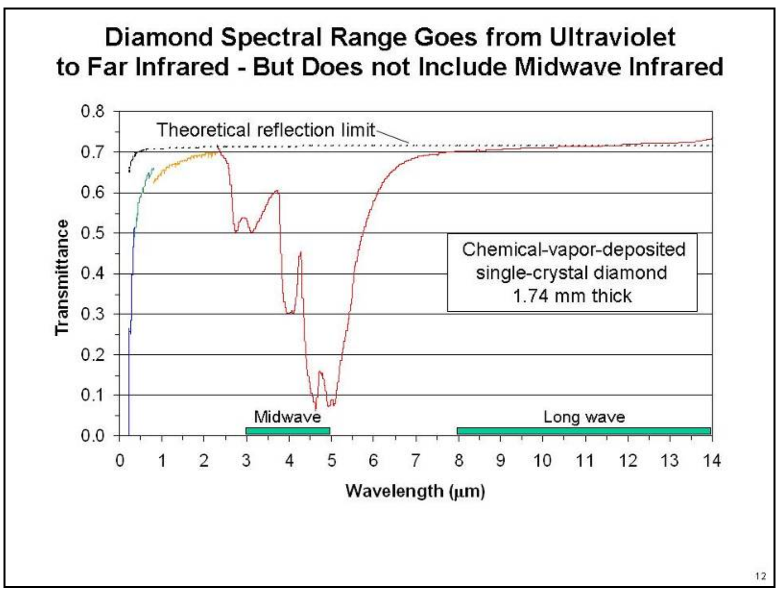

Figure 172. Spectral transmittance versus wavelength of a chemical vapor deposited diamond.

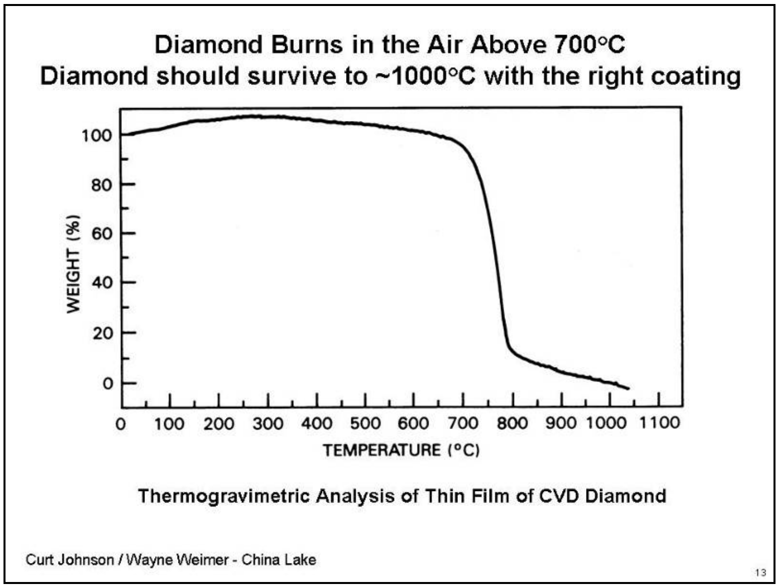

Figure 173. Thermal degradation of diamond in air.

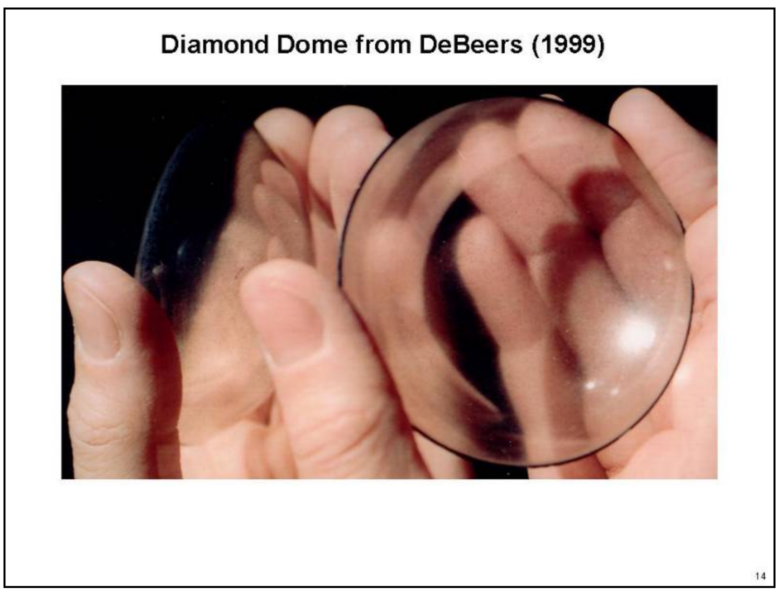

Figure 174. Diamond domes manufactured by DeBeers.

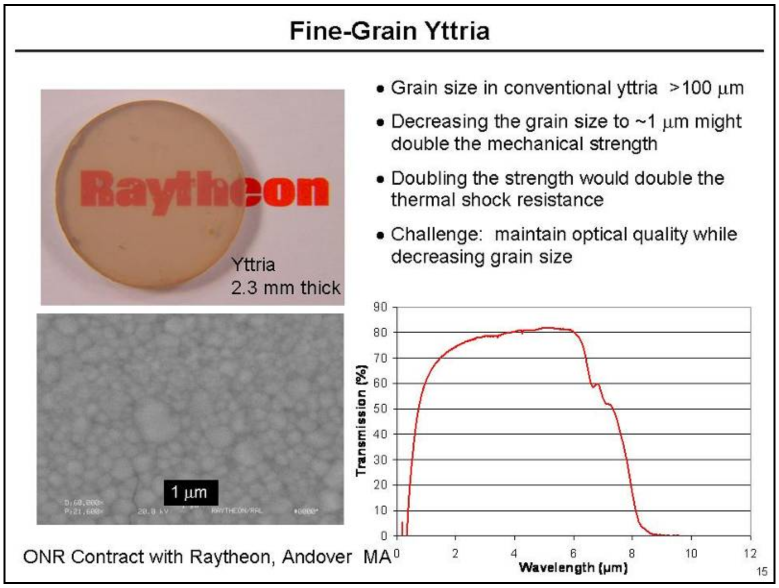

Figure 175. Fine-grain Yttria disks and the transmittance.

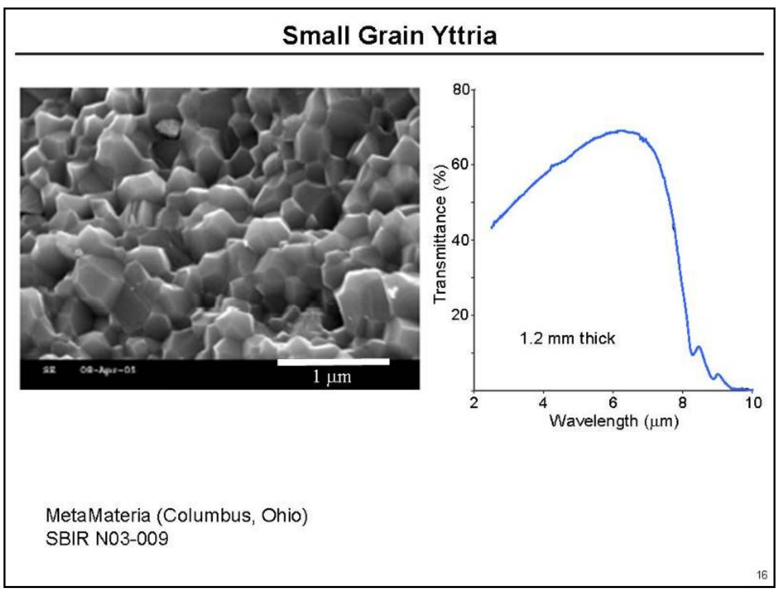

Figure 176. Microstructure of small-grain yttria and transmittance.

Optical Nano-composite
An Oxymoron?

- Composites might offer new mechanical properties not available in monolithic materials (eg., higher toughness, strength, hardness)
- Composites possess far more grain boundary than monolithics. Grain boundaries are responsible for optical absorption and scatter
- Micron grain size composites scatter too much light to be used as windows
- If grain size is much smaller than wavelength of light, scatter could be reduced
- The "gold standard" is sapphire. We want to improve on some property of sapphire, such as toughness, thermal shock resistance, longer wave transmission, or cost

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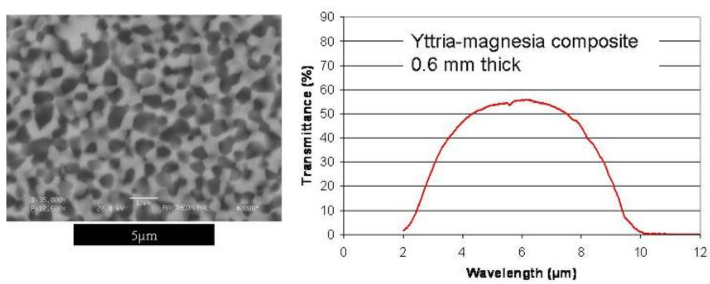
Figure 177. Is an optical nanocomposite just an oxymoron or is it technically possible?

Nanograin Yttria-Magnesia Composite



ONR Contract with Raytheon Andover
Collaboration with Rutgers University

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Figure 178. Nano-yttria-magnesia composite with transmission curve.

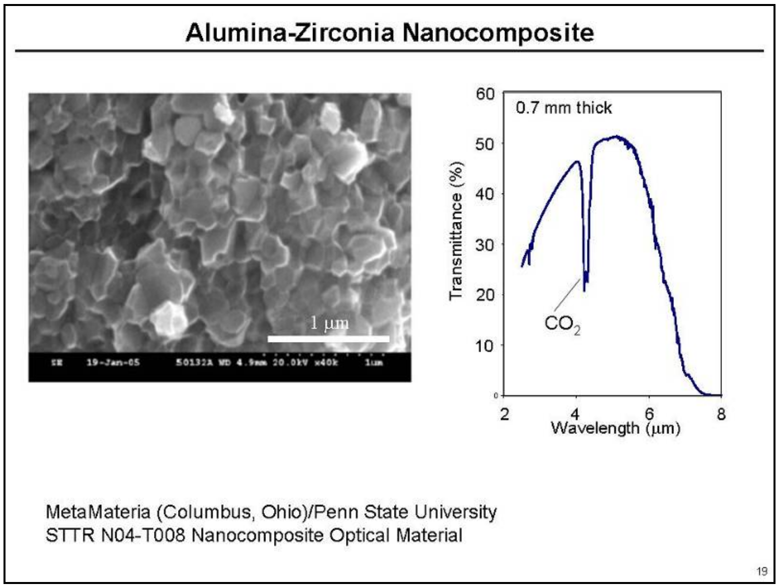

Figure 179. Alumina-zirconia nanocomposite and transmission curve.

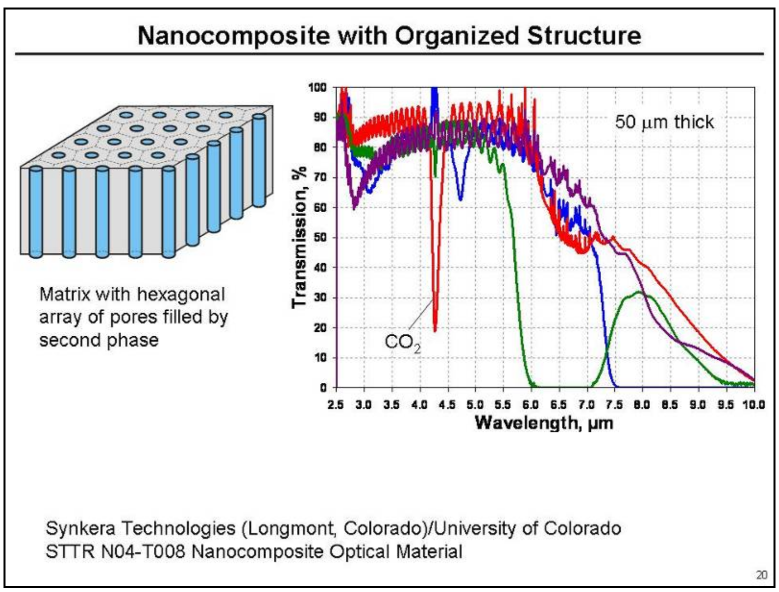

Figure 180. Concept cartoon for nanocomposite of highly organized structure and computationally generated transmission curves.

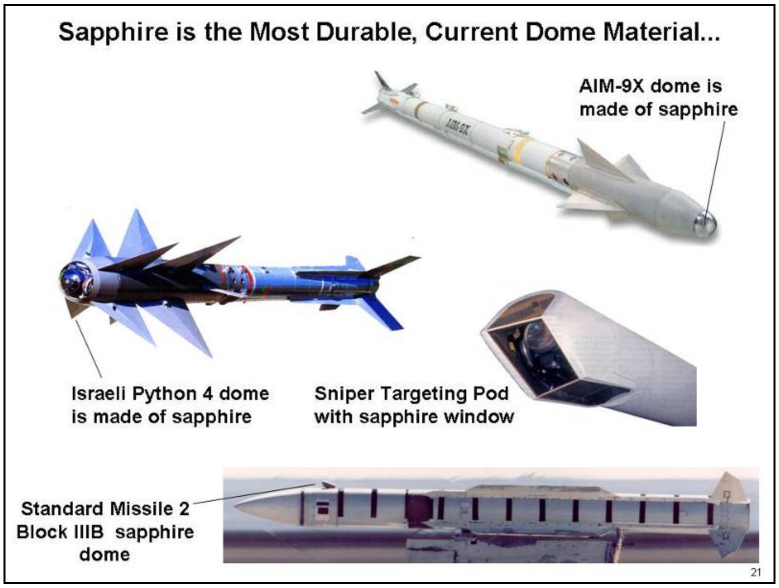

Figure 181. Sapphire applications of dome materials.

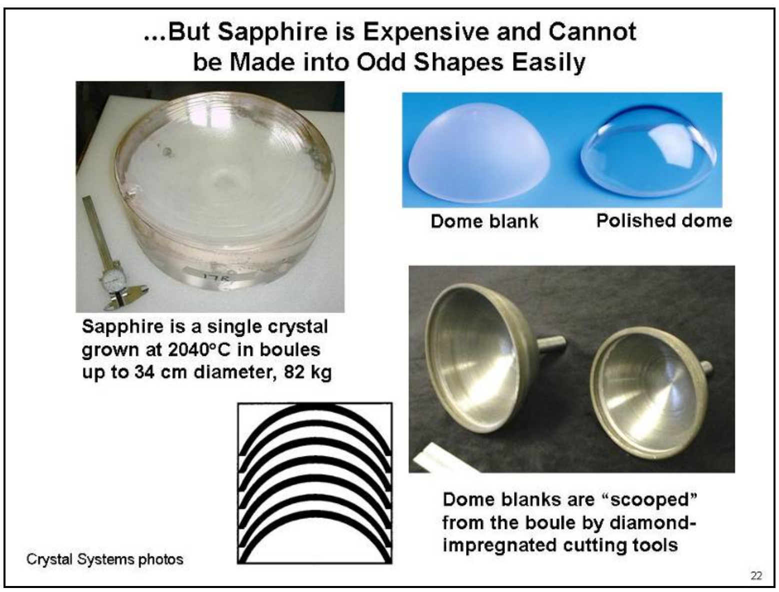

Figure 182. How sapphire is made for dome applications currently.

Figure 183. Transparent alumina as a possible sapphire replacement.

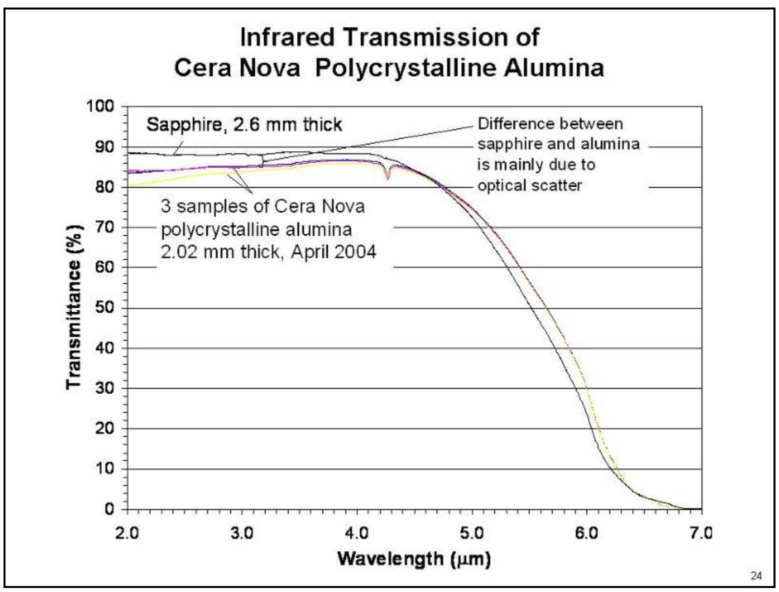

Figure 184. Infrared transmission of PCA.

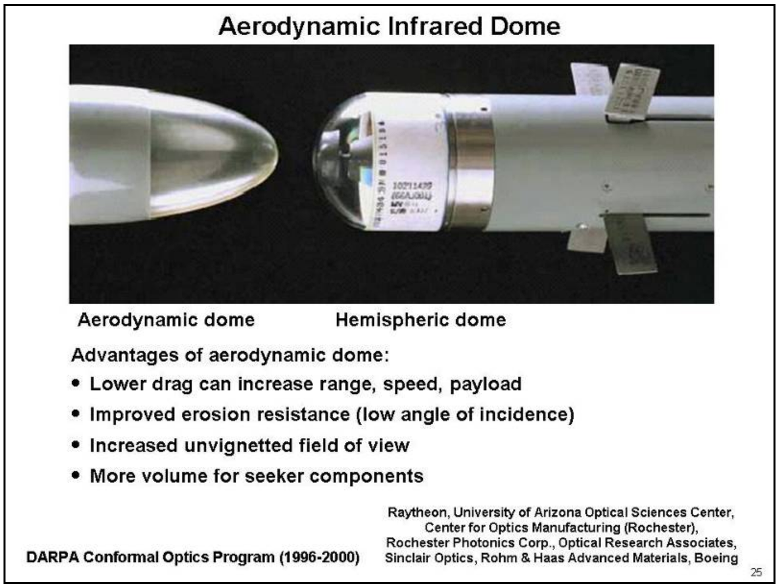

Figure 185. Aerodynamics of infrared domes.

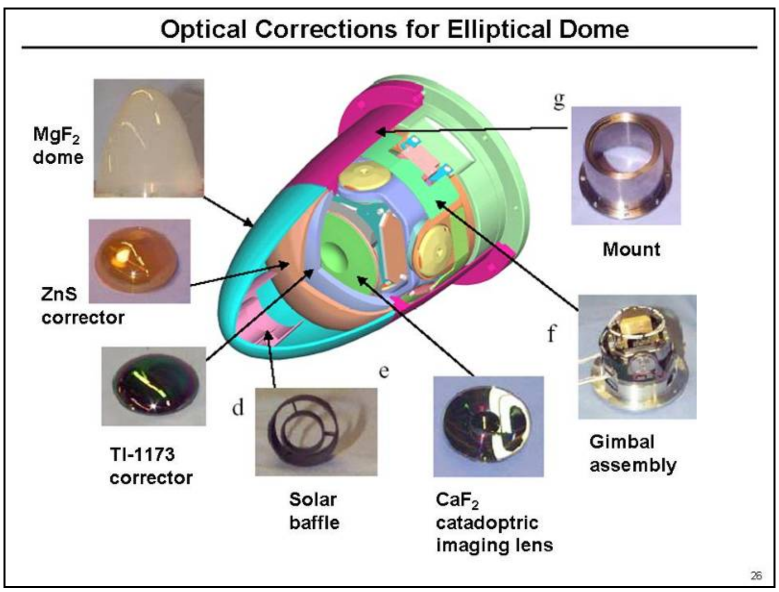

Figure 186. Optical corrections for elliptical domes.

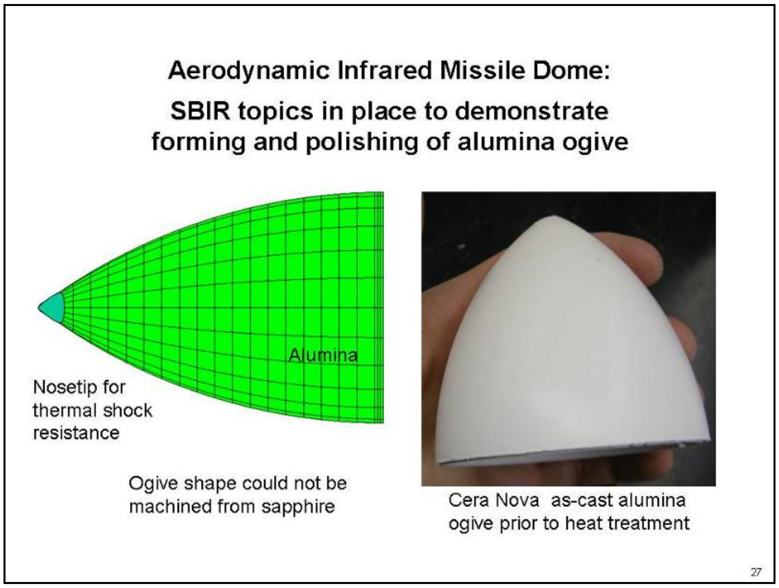

Figure 187. Aerodynamics of infrared missile domes.

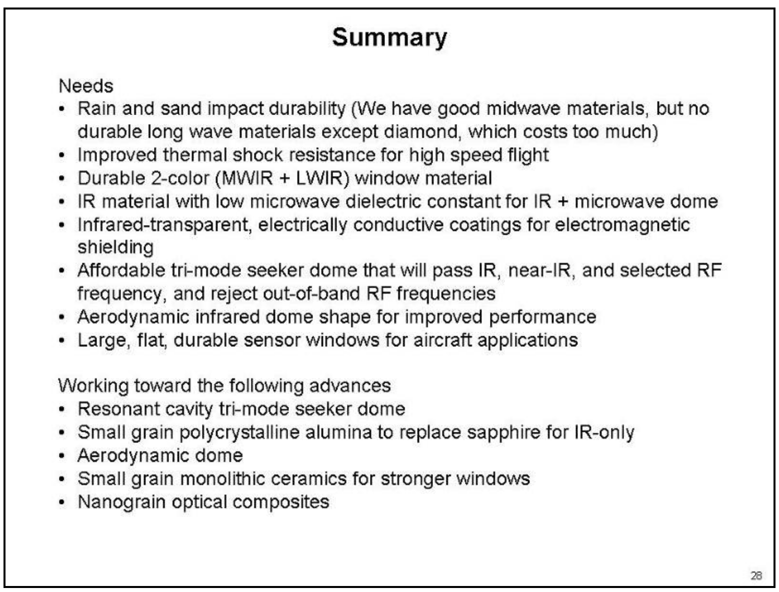

Figure 188. Summary of needs and approaches in dome technology.

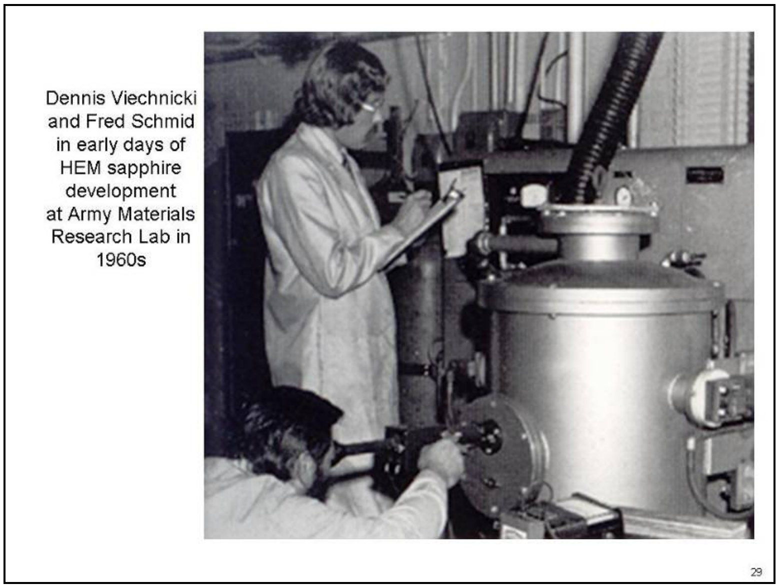

Figure 189. Early photograph of some colleagues from days in the laboratory; shown are Dr. Viechnicki and Dr. Schmidt.

8. Conclusions

The Sagamore Army Materials Research Conferences continue to bring together scientists and engineers from government, industry, and universities for in-depth discussions of cutting edge materials technology issues of critical importance to the Army community. In 2004, the need for improved technical advancements in transparent materials was identified as a key technology gap for the U.S. Army. The objective of the 46th Sagamore Army Materials Research Conference held May 9–12, 2005, was to review the applications, requirements, and major technical barriers of multi-spectral transparent materials for sensor protection, ground and air vehicle ballistic protection, personnel protection, and infrastructure survivability. The meeting successfully demonstrated the effectiveness of the U.S. industrial, government, and academic sectors to provide technology solutions that will allow the Army to move forward into advanced platform developments, such as the Future Combat Systems and Unit of Action deployment concepts.

Session I set the tone for this historic conference event. ARL leadership opened the conference by offering examples of Army partnerships that resulted in technical breakthroughs that directly impact the Soldier. The season of war in the Middle East region has resulted in escalated insertion needs that are being met with technologies that existed but had not been pushed forward. The realization of the need for more rapid insertions is highlighted. Next, an Army Soldier presented a touching story of needs and impact on the lives of Soldiers. Major Rusin showed numerous examples of platforms and the extended use of these vehicles beyond their design intentions in the war environment. The Major further called for industry to develop next generation transparencies for vehicles at an accelerated pace to increase the potential to return Soldiers safely from battleground encounters to their families. He also emphasized the huge logistics challenge that the Army is facing with such a massive deployment effort and emphasized the importance of making technologies available and multifunctional.

Continuing the military perspective, Dr. Coryell offered insights into next generation communications technologies and the importance of this area for future Army mobility concepts. Of particular concern is the limited technology available to protect communications devices. An industrial perspective on laser host materials was provided by a key industrial leader from Raytheon, Dr. Gentilman. Raytheon continues to develop advanced ceramic materials to meet the demands for high energy lasers by exploring laser ceramic hosts. Finally, the Navy's Dr. Harris discussed the critical field of advanced seekers and the goals of seekers for multi-spectral performance in the future. Specifically, Dr. Harris emphasized the development of tri-mode seeker technology that puts a tremendous burden on the materials community to offer durable dome solutions. The session concluded with a question-and-answer session that set the tone for a good technical meeting.

Session II was a focused session specifically looking at the technical challenges for advanced tracking and communications technologies. The session included three speakers from government and industry sources that offered insights into the future of missile technology and the limitations of current materials.

Session III was a rare opportunity to explore the impact of small businesses in the transparent materials development community. The leaders in many small market ceramics presented their technical insights and views on the growth potential for transparent ceramic markets. The industry members included representatives for sapphire, aluminum oxynitrde ceramics, and spinel ceramics. One member even presented the concept of transparent alumina by developing small-grain alumina. These presenters offer a glimpse into the ingenuity that exists through the vast small business network that exists in the United States. The group collectively fielded questions about the potential for these high-cost, low-volume ceramics to be made readily available for large aperture and large volume needs such as military windows and domes.

Session IV was the most diverse technology session. The focus of this session was around multi-functional electromagnetic materials. The presenters included members of the academic communities most noted for their impacts in transparent materials and a key representative from one of the largest transparency suppliers in the United States, Pittsburgh Plate and Glass (PPG). The take-home message from these offerings was that materials technologies have only begun to illuminate the concepts that could become tomorrow's technology wizardry. The presenters demonstrated an extensive exposure to various fields not currently part of the transparent materials focus for the military.

The most attended session of the week is Session V, entitled “Transparent Armor: Needs and Future Challenges.” The session included three key briefings that considered the needs for transparencies for ground vehicles and aircraft. An effort was also given to look at the economic impact of the high-cost ceramic materials being evaluated for future military armors. At the conclusion of the session, the audience was invigorated to look deeply into how to move technologies forward to market to better serve the Soldiers in harms way.

Continuing the theme of transparent armors, Session VI, explored the latest in testing and performance of some commercial transparent materials. Materials presented included cutting edge polymer materials, high-cost transparent ceramics, and hybrid concepts such as glass-ceramics that offer intermediate performance and costs between traditional glass and transparent ceramics. Two authors from this session graciously provided manuscripts for their concepts that are included as part of this report. Dr. Bless provided an extensive look into the damage mechanisms involved in fracture of glass laminate materials. His fine contribution shows the importance of analysis in determining the mechanisms for failure in thick glass armors. The results from his study offered new insights for how to design future armors using traditional low-cost glass and plastic materials available through the commercial supply chains. These concepts are the most likely to result in rapidly fielded armor solutions, due to materials readiness and understanding of performance limits. Dr. S.-W. Lee also offered a manuscript that demonstrated the challenges associated with creating new transparent ceramic materials. His contribution on polycrystalline silicon nitride shows how important and varied the field of transparent materials can be. He provided a detailed study of how to fabricate and characterize the variables impacting transparency in never before developed transparent ceramics. The session offered the greatest diversity and netted some of the most extensive questions of the meeting. The session culminated with the keynote speaker who offered a great history of the Sagamore conference series and encouraged future interactions to make the meeting a success.

Finally, Session VII concluded the meeting with a very detailed look into the field of laser host materials. Specifically, many of the participants are attempting to achieve a U.S. source for the known transparent ceramics produced by Konoshima. Many of the companies presenting are small business ventures whose resources are provided under various small business innovation funding lines by the military customer. The ever-growing need for advanced laser technology for commercial applications such as cutting, grinding, polishing, and machining has opened a significant opportunity for dual-use technologies such as laser hosts. The military is interested in high energy laser materials that will allow higher throughput and higher energy density in smaller areas. Current commercial sources of lasing materials rely on YAG materials that are grown as single crystals and doped for lasing purposes. The session looked intently into the approaches to transparent ceramic laser host technologies as alternatives to YAG for improved performance and reliability.

At the end of the multi-day exchange, the 50^{th} Anniversary celebration of the Sagamore Army Materials Research Conferences explored the gaps in transparent armor, phased array radar, displays, electromagnetic windows and domes, and polycrystalline lasers. The result of this meeting is new understanding of the processing, characterization, property testing, and system requirements for advanced ceramic and polymer systems relevant to military system performance. In general, the briefings provided by the attendees and the forum providing for technical exchange allowed numerous new projects and programs to be initiated that are shaping the future of transparent materials for military applications. The Army gratefully acknowledges that the United States has a capable technology base to provide for the needs of the Soldier for years to come.

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Appendix. Attendee List

This appendix includes a photo (figure A-1) and a full list of the attendees (table A-1).

Figure A-1. Attendees from the 46th Sagamore Army Materials Research Conference.

Table A-1. Attendees list from the 46th Sagamore Army Materials Research Conference.

Last Name	First Name	Title	Org	Address	City, State Zip
Aggarwal	Ishwar	Dr.	Naval Research Laboratory	Code 5606	Washington, DC 20375-5338
Amarakoon	Vasantha	Director	Alfred University	New York State College of Ceramics, 2 Pine St	Alfred, NY 14802
Arrasmith	Steven	Assistant Director	Alfred University	New York State College of Ceramics, 2 Pine St	Alfred, NY 14802
Askinazi	Joel	Chief Engineer Advanced Window Development	Goodrich Electro Optical Systems	100 Wooster Heights Road	Danbury, CT 06810
Avery	Terrance	Mechanical Engineer	U.S. Army RDECOM-TARDEC	6501 E. Eleven Mile Road	Warren, MI 48397-5000
Bepko	Stephen	Senior Advisory Engineer	Northrop Grumman Electronic Systems	1745A West Nursery Road, Mail Stop 368	Linthicum, MD 21090
Beyer	Rick	Dr.	U.S. Army Research Laboratory	AMSRD-ARL-WM-MA	Aberdeen Proving Ground, MD 21005
Bless	Stephan	Senior Research Scientist	IAT at University of Texas at Austin	3925 West Braker Lane, Suite 400	Austin, TX 78759-5316
Bowen	Leslie	President	Materials Systems, Inc.	543 Great Road	Littleton, MA 01460
Coleman	Karen	Assistant Director	Zimmerman Associates, Inc.	1401 Wilson Boulevard, Suite 100	Arlington, VA 22209
Coryell	Louis	Team Leader	CERDEC Space & Terrestrial Communications Dir.	AMSRD-CER-ST-SS-TA	Fort Monmouth, NJ 07703
Dehmer	Peter	Materials Engineer	U.S. Army Research Laboratory	AMSRD-ARL-WM-MD	Aberdeen Proving Ground, MD 21005

Table A-1. Attendees list from the 46th Sagamore Army Materials Research Conference (continued).

Last Name	First Name	Title	Org	Address	City, State Zip
Deitzel	Joseph	Dr.	University of Delaware, Center for Composite Materials	201 Composite Manufacturing Science Laboratory	Newark, DE 19716
Dowding	Robert	Mr.	U.S. Army Research Laboratory	AMSRD-ARL-WM-MB	Aberdeen Proving Ground, MD 21005-5069
Dubinskiy	Mark	Dr.	U.S. Army Research Laboratory	AMSRD-ARL-SE-EO, 2800 Powder Mill Road	Adelphi, MD 20783
Dulcos	Steve	Dr.	GE	K1-MB159, One Research Circle	Niskayuna, NY 12309
Eilers	Hergen	Associate Director	Washington State University	P.O. Box 1495	Spokane, WA 99210
Endres	Berkan	Dr.	3M Company	3M Center, Building 251-1A-03	St. Paul, MN 55144
Everson	William	Mr.	Penn State Electro-Optics Center	559A Freeport Road	Freeport, PA 16229
Fehrenbacher	Larry	Dr.	TA&T, Inc.	133 Defense Highway, Suite 212	Annapolis, MD 21401
Folgar	Francisco	Director	INTER Materials, LLC	623 Muirfield Court	Richmond, VA 23236
Foster	Rick	Commercial Development Manager	Materials Systems, Inc.	543 Great Road	Littleton, MA 01460
Fuller	Joan	Dr.	AFOSR	875 North Randolph Street, Suite 325, Room 3112	Arlington, VA 22203
Gentilman	Richard	Senior Engineering Manager	Raytheon Company – Integrated Defense Systems	350 Lowell Street	Andover, MA 01810
Gilde	Gary	Ceramic Engineer	U.S. Army Research Laboratory	AMSRD-ARL-WM-MC	Aberdeen Proving Ground, MD 21005-5069
Ginley	David	Group Manager	National Renewable Energy Lab	1617 Cole Boulevard, Mail Stop 3211	Golden, CO 80401
Goldman	Lee	Dr.	Surmet Corporation	33 B Street	Burlington, MA 01803
Green	David	Professor	The Pennsylvania State University	230 Steidle	University Park, PA 16802
Grethlein	Chris	Deputy Director	AMPTIAC – Alion Science & Technology	201 Mill Street	Rome, NY 13440
Grum	Allen	Associate Director for Strategic Initiatives	U.S. Army Research Laboratory	2800 Powder Mill Road	Adelphi, MD 20783-1197
Haber	Richard	Director, Center for Ceramic Research	Rutgers, The State University of New Jersey	607 Taylor Road	Piscataway, NJ 08854
Haertling	Gene	Professor Emeritus	Retired Clemson University	9512 Layton Place, NE	Albuquerque, NM 87111
Harris	Daniel	Senior Scientist	Naval Air Systems Center	1900 North Know Road, Mail Stop 6303	China Lake, CA 93555-6106
Herzog	Mathew	Materials Engineer	NASA Langley Research Center	6 West Taylor Street	Hampton, VA 23681-0001
Hong	William	Research Staff/Assistant Director	Institute for Defense Analyses	4850 Mark Center Drive	Alexandria, VA 22311
Hood	Robert	Team Leader, Subsystems	Aviation Applied Technology Directorate	AMSRD-AMR-AA-F	Fort Eustis, VA 23604-5577
Hsieh	Alex	Materials Research Engineer	U.S. Army Research Laboratory	AMSRD-ARL-WM-MD	Aberdeen Proving Ground, MD 21005-5069
Jensen	Robert	Research Chemist	U.S. Army Research Laboratory	AMSRD-ARL-WM-MB	Aberdeen Proving Ground, MD 21005-5069
Johnson	Warren	Program Manager	Universal Technology Corporation	1270 North Fairfield Road	Dayton, OH 45432-2600

Table A-1. Attendees list from the 46th Sagamore Army Materials Research Conference (continued).

Last Name	First Name	Title	Org	Address	City, State Zip
Khattak	Chandra	Dr./Executive Vice President	Crystal Systems, Inc.	27 Congress Street	Salem, MA 01970
Kim	Sang Woo	Senior Research Scientist	Korea Institute of Science and Engineering	39-1 Hawolgok-dong	Sungbuk, Seoul 136-791
Kop	Theo	Dr.	Philips Research	High Tech Campus 4 (WAG12)	Eidenhoven, 5656 AE
Kostyk	Barry	Dr.	3M Company	3M Center, CRBA , Building 235-E330	St. Paul, MN 55144
LaCourse	William	Professor of Glass Science	Alfred University	New York State College of Ceramics, 2 Pine St	Alfred, NY 14802
Lee	HeeDong	Materials Research Scientist	UES, Inc.	4401 Dayton-Xenia Road	Dayton, OH 45432-1894
Lee	Soo Wohn	Professor	Sun Moon University	100, GalSan-Ri-, TangJung-Myon	Asan, ChungNam 336-708
Lesser	Alan	Professor	University of Massachusetts	Polymer Science & Engineering Department	Amherst, MA 01003
Loureiro	Sergio	Dr.	General Electric	One Research Circle, K-1 MB149	Niskayuna, NY 12309
Mah	Tai-il	Materials Research Scientist	UES, Inc.	4401 Dayton-Xenia Road	Dayton, OH 45432-1894
Manghnani	Murli	Professor	University of Hawaii, Hawaii Institute of Geophysics & Planetology	2525 Correa Road	Honolulu, HI 96822
Manoharan	Mohan	Dr.	GE Global Research	One Research Circle	Niskayuna, NY 12309
Martin	Curtis	Mr.	Naval Surface Warfare Center, Carderock Division	9500 MacArthur Boulevard	West Bethesda, MD 20817
McCauley	James	Executive Co-Chair	U.S. Army Research Laboratory	4600 Deer Creek Loop	Aberdeen Proving Ground, MD 21005-5069
McCloy	John	Senior Materials Engineer	Raytheon Missile Systems	1151 E. Hermans Road, Building 840, Mail Stop 6	Tucson, AZ 85730
Messing	Gary	Dr.	Pennsylvania State University	121 Steidle Building	University Park, PA 16802
Miller	John	Senior Account Manager, Military Programs	PPG Industries, Inc.	P.O. Box 040004	Huntsville, AL 35804
Mishra	Amar	Associate Director	PPG Industries, Inc.	P.O. Box 11472	Pittsburgh, PA 15238
Moloney	Michael	Senior Program Officer	National Materials Advisory Board	500 Fifth Street, NW	Washington, DC 20001
Moncur	Marlowe	Director, R&D	GKN Aerospace Transparency Systems	12112 Western Avenue	Garden Grove, CA 92841
Myers	Duane	Principal Engineer	Directed Technologies, Inc.	3601 Wilson Boulevard, Suite 650	Arlington, VA 22201
Niesz	Dale	Professor	Rutgers University	607 Taylor4 Road	Piscataway, NJ 08854-8065
Parthasarathy	Triplicane	Materials Research Scientist	UES, Inc.	4401 Dayton-Xenia Road	Dayton, OH 45432-1894
Pascucci	Marina	Dr.	CeraNova Corporation	85 Haynes Memorial Drive	Marlborough, MA 01752
Patel	Parimal	Dr.	U.S. Army Research Laboratory	AMSRD-ARL-WM-MD	Aberdeen Proving Ground, MD 21005-5069
Pennisi	Licio	Assistant Director	Alfred University	New York State College of Ceramics, 2 Pine Street	Alfred, NY 14802
Procurat-Franks	Lisa	Ms.	U.S. Army TARDEC	Mail Stop 263; 6501 E. 11 Mile Road	Warren, MI 48397-5000
Quarles	Gregory	Director of Research	VLOC Inc.	7826 Photonics Drive	New Port Richey, FL 34655

Table A-1. Attendees list from the 46th Sagamore Army Materials Research Conference (continued).

Last Name	First Name	Title	Org	Address	City, State Zip
Randi	Joseph	Dr.	Penn State Electro-Optics Center	222 Northpointe	Freeport, PA 16229
Rhodes	William	Dr.	Rhodes Consulting	4 McKeever Drive	Lexington, MA 02420
Riman	Richard	Professor	Rutgers University	607 Taylor Road	Piscataway, NJ 08854
Robinson	Barry	Production Manager	Materials Systems, Inc.	543 Great Road	Littleton, MA 01460
Rusin	Daniel	Major	U.S. Army Research Laboratory	AMSRD-ARL-WM-TA	Aberdeen Proving Ground, MD 21005-5069
Sands	James	Dr.	U.S. Army Research Laboratory	AMSRD-ARL-WM-MD	Aberdeen Proving Ground, MD 21005-5069
Sastri	Suri	Dr.	Surmet Corporation	33 B Street	Burlington, MA 01803
Scerbak	David	Dr.	Electro-Optics Technology	5835 Shugart Lane	Traverse City, MI 49684
Scott	Brian	Dr.	U.S. Army Research Laboratory	AMSRD-ARL-WM-MD	Aberdeen Proving Ground, MD 21005-5069
Sennett	Michael	Dr.	U.S. Army RDECOM Natick Soldier Center	15 Kansas Street	Natick, MA 01760
Smith	Jill	Ms.	U.S. Army Research Laboratory	AMSRD-ARL-WM	Aberdeen Proving Ground, MD 21005-5069
Song	John	Materials Research Engineer	U.S. Army Natick Soldier Center	15 Kansas Street	Natick, MA 01760
Sullivan	Roger	Dr.	Naval Air Systems Center	1900 North Knox Road, Mail Stop 6303	China Lake, CA 93555-6106
Sung	Rakjoo	Researcher	Korea Institute of Science and Engineering	39-1 Hawalgok-dong	Sungbuk, Seoul 136-791
Sutorik	Anthony	Dr.	Nanocerox	712 State Circle	Ann Arbor, MI 48108
Swanson	Stephen	CEO	Nanocerox	712 State Circle	Ann Arbor, MI 48108
Tustison	Randy	Dr.	Raytheon Company - Integrated Defense Systems	350 Lowell Street, Mail Stop ANF B16	Andover, MA 01810
Vala	John	Mr.	U.S. Army RDECOM-TARDEC	6501 E. Eleven Mile Road	Warren, MI 48397-5000
Van Allen	Derek	Materials Engineer	NASA Langley Research Center	6 West Taylor Street, Mail Stop 227	Hampton, VA 23681-0001
Varshneya	Arun	Professor of Glass Science & Engineering	Alfred University	New York State College of Ceramics, 2 Pine St	Alfred, NY 14802
Venkataramani	Venkat	Sr. Materials Scientist	General Electric Global Research Center	K-1; MB 167, 1 Research Circle	Niskayuna, NY 12309
Viechnicki	Dennis	Consultant	Consultant	5 Poplar Road	Wellesley, MA 02482
Wang	King	Principal Scientist	Agiltron, Inc.	15 Cabot Road	Woburn, MA 01801
Weiss	Volker	Professor Emeritus	Syracuse University	238 Scottholm Terrace	Syracuse, NY 13224
Wienhold	Carsten	Mr.	Schott North America - Regional R&D	400 York Avenue	Duryea, PA 18642-2036
Willardson	Rick	Sr. Mechanical Engineer	Raytheon Electronic Systems	2501 W. University Drive, M/S 8019	McKinney, TX 75071-2813
Wolfe	Gregory	Mr.	U.S. Army TARDEC	6501 East Eleven Mile Road, AMSRD-TAR-R, MS 263	Warren, MI 48397-5000
Yu	Kevin	Director	Physical Optics Corporation	20600 Gramercy Place, Bldg. #100	Torrance, CA 90501
Zhang	Jay	Manager, Government Techology & Business Dev.	Corning, Inc.	One Science Center Drive, SP-FR-02-10	Corning, NY 14831

Acronyms

AlN	aluminum nitride
AlON	aluminium oxynitride
AMMRC	Army Materials & Mechanics Research Center
AMRDEC	Aviation & Missile Research, Development, and Engineering Center
AoA	add-on-armor
APG	Aberdeen Proving Ground
APS	Average Particle Size
ARL	U.S. Army Research Laboratory
ARO	Army Research Office
AROD	Army Research Office – Durham
Au	gold
CERDEC	Communications-Electronics Research Development and Engineering Center
COTM	Communications on the move
DoD	Department of Defense
ESP	engineered stress profile
FSP	flame spray pyrolysis
FWs	Failure Waves
HIP	hot isostatic pressed
HMMWV	Up Armored High Mobility Multi-purpose Wheeled Vehicle
HPSSL	high-power solid state lasers
In	indium
JCPDS	Joint Committee on Powder Diffraction Standards
La	Lanthanum
MgO	magnesium oxide

MIT	Massachusetts Institute of Technology
Nd:YAG	neodymium: yttrium aluminum garnet
O	oxygen
OEF	Operation Enduring Freedom
OIF	Operations Iraqi
OMRO	Ordnance Materials Research Office
OOR	Office of Ordnance Research
ORMSOL	Organically Modified Sol-gel
PCA	polycrystalline alumina
PLZTs	polarized lead zirconium titanates
PMMA	polymethylmethacrylate
PMN-PT	lead magnesium niobate-lead titanate
POC	Physical Optics Corporation
PU	polyurethane
PZN-PT	lead zinc niobate-lead titanate
R&D	research and development
RDECOM	Research Development and Engineering Command
S&T	Science and Technology
SATCOM	Satellite Communications
SBIR	Small Business Innovation Research
SEM	scanning electron microscope
Si_3N_4	silicon nitride
SiC	silicon carbide
SLS	soda-lime-silicate
SU	Syracuse University
TARDEC	Tank and Automotive Research, Development and Engineering Center
TCOs	transparent conducting oxides

TMA	Transparent Multifunctional Armor
TWV	Tactical Wheeled Vehicle
XRD	X-ray diffraction
YAG	yttrium aluminum garnet
Zn	zinc

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